Application No.: 09/833452
Docket No.: AD6728USNA

Applicants' claims 1, 6, and 67-68 recite as follow. The emphases are added by applicants.

1. A multila yer film or sheet comprising:
a.) a first *co-extruded* polymeric layer consisting essentially of an ionomer and a first additive; and
b.) a second *co-extruded* polymeric layer consisting of an ionomer and a second additive;
wherein the film or sheet is a thermoformable film or sheet having a thickness in the range of from about 8 mils to about 60 mils; *the first co-extruded polymeric layer is surface layer*; the second co-extruded layer is in contact with said first co-extruded polymeric layer; and the first or second additive is one or more UV stabilizer, UV absorber, antioxidant, thermal stabilizer, anti-stat additive, processing aid, fiber glass, mineral filler, anti-slip agent, plasticizer, nucleating agent, pigment, dye, flake, or mixtures thereof.

6. A multilayer film or sheet of Claim 1 wherein said *first co-extruded polymeric layer is clear* and said second co-extruded polymeric layer comprises the polymer and an additive selected from pigment, dye, flake, or mixtures thereof.

67. The multilayer film or sheet of claim 6 wherein the ionomer in the first co-extruded polymeric layer and the ionomer in the second co-extruded polymeric layer have flow properties that are matched to allow the ionomer in the first co-extruded layer and the ionomer in the second co-extruded polymeric layer, *when co-extruded, flow to the full width of the die*.

68. The multilayer film or sheet of claim 59 wherein the ionomer in the first co-extruded polymeric layer and the ionomer in the second co-extruded polymeric layer have flow properties that are matched to allow the ionomer in the first co-extruded layer and the ionomer in the second co-extruded polymeric layer, *when co-extruded, flow to the full width of the die*.

Claims 69-72 indirectly depend from claims 1, 6, and/or 67-68 with intervening limitations. That is, claims 69-72 require at least these limitations: (1) two coextruded layers; (2) the first co-extruded layer must be a surface layer; (3) each layer contains at least one additive; (4), for claims 70-72, the first co-extruded polymeric layer is surface layer; and (5), for claims 71-72, the ionomer in the first co-extruded polymeric layer and the ionomer in the second co-extruded polymeric layer have flow properties that are matched to allow the ionomer in the first co-extruded layer and the ionomer in the second co-extruded polymeric layer, when co-extruded, flow to the full width of the die.

The Smith films 77 including pigmented layer 73 are disclosed in FIGS. 11(a)-11(i) (column 9, line 6 to column 11, line 6). Smith Figures 11(a)-11(i) show that 11(a)-11(e) are extruded. The rest, i.e., 11(f)-11(i) are done by post-extrusion lamination.

Because 11(f)-11(i) are not extruded films, they are not further discussed below.

Application No.: 09/833452
Docket No.: AD6728USNA

Now, referring to the Smith extruded (FIGS.) 11(a)-11(e), applicants prepare the following table for the examiner's easy comparison.

| Smith Films | Comments |
|---|---|
| 11(a): approximately planar sheet of color pigmented and metallized thermoplastic layer 73 | Mono-extruded film layer, not coextruded layers of ionomers. |
| 11(b): coextruded sheet 77 includes pigmented/ metallized thermoplastic material 73 and optional tie layer 75 bonded to one another. | Applicants' claim 1 does not recite a first layer with a tie layer. |
| 11(c): coextruded sheet 77 includes layer 73, optional tie layer 75, and clearcoat 79 bonded to one another. | The clearcoat layer 79 does not contain additives in all its embodiments. |
| 11(d): coextruded sheet 77 includes color layer 73, optional tie layer 75, and optional clearcoat 79 and optional protective coating layer 81 provided over the clear coat layer. | Layer 79 is not surface layer |
| 11(e): coextruded sheet 77 includes layerl 73, optional tie layer 75, and optional clearcoat 79, optional tie layer 83 and optional removable protective coating layer 81. | The two coextruded layers (73 and 79) teach away from claims 1 in that there is described a tie layer between both coextruded layers |
| 11(b)-11(e) Except layer 73, all other layers are optional | |

Only 11(c) shows that a *coextruded* layer 79 is surface layer and layer 73 is in contact with the surface layer.

That is, Smith shows that, out of the 9 different films disclosed, only 11(c) shows that a *coextruded* layer 79 is surface layer and layer 73 is in contact with the surface layer AND that out of at least 14 (not counting the combinations) of additives, only pigment is disclosed in the clear layer 79.

One skilled in the art cannot "at once envisage" claim 69-72 from the Smith disclosure. By analogy, this meets the criterion enunciated in MPEP 2131.03 (If the claims are directed to a narrow range, the reference teaches a broad range, and there is evidence of unexpected results within the claimed narrow range, depending on the other facts of the case, it may be reasonable to conclude that the narrow range is not disclosed with "*sufficient specificity*" to constitute an anticipation of the claims).

Secondly, as discussed above, applicants' claims 70-72 directly or indirectly depend from claim 6, which calls for the surface layer being clear layer. Claims 70-72 also require that the surface layer be clear.

The only additive that may be present in the clear coat layer 79 is pigment. *See* column 17, lines 30-34.

To the contrary, applicants' claims require that the first co-extruded polymeric layer not only be clear (no pigment), but also consist essentially of an ionomer and a first

Application No.: 09/833452
Docket No.: AD6728USNA

*additive*, which is one or more UV stabilizer, UV absorber, antioxidant, thermal stabilizer, anti-stat additive, processing aid, fiber glass, mineral filler, anti-slip agent, plasticizer, nucleating agent, pigment, dye, flake, or mixtures thereof.

Smith layer 79 contains a pigment, but no other additive and, therefore, cannot anticipate claim s 70-72.

Thirdly, Smith film 11(c) does not disclose that "the ionomer in the first co-extruded polymeric layer and the ionomer in the second co-extruded polymeric layer have flow properties that are matched to allow the ionomer in the first co-extruded layer and the ionomer in the second co-extruded polymeric layer, when co-extruded, flow to the full width of the die", limitation recited in claims 71-72.

Therefore, Smith does not anticipate claims 71-72.

Fourthly, claims 69-72 have a common limitation that the first coextruded film or sheet has distinctiveness of image of at least 80.

The only disclosure of distinctiveness of image in Smith is at column 19, lines 58-64, which is copied below.

> Distinctiveness of image (DOI) is a measurement of the clarity of an image reflected by the finished surface. Each of these products/parts *may* have a DOI of at least about 60 units, where 100 is the maximum DOI reading, measured by a Hunter Lab, Model No. D47R-6F Dorigon gloss meter. Details of this DOI test procedure are described in GM test specification GM-204-M which is incorporated herein by reference.

Smith discloses that the product *may* have a DOI of at lest about 60 units. However, Smith does not disclose that the DOI is at least 80. A product that *may* have a DOI of at least 60 does not mean it should have at least 80.

As the examiner noted, Smith discloses that 100 is the maximum DOI reading measured by Hunter Lab meaning the maximum DOI measure by Hunter Lab is 100. This is well known to one skilled in the art that the maximum scale of DOI value is 100.

An analogy to the Smith disclosure as follows. USPTO requires that Jones work for the USPTO for at least 250 days a year and a year has a maximum days of 365 (except every other 4 years). Does that mean the USPTO requires that Jones work at least 300 days a year?

Using the analogy, one skilled in the art would discern that Smith merely discloses at least 60 DOI, but does not disclose that the product shown therein have a DOI of maximum value of 100 or at least 80, as recited in applicants' claims.

Application No.: 09/833452
Docket No.: AD6728USNA

Fifthly, even assuming, *arguendo*, that Smith did disclose an DOI of at least 80, Smith does not disclose the combination of a DOI of at least 80 and a gloss that exceeds 60% at a 20 degree angle, which are the limitation recited in claims 69-72. That is, Smith does not require both conditions be met simultaneously.

**Rejection of claims 1, 3, 6, 43, 54-55, 57-63 (should be 60), 65 (should be 66)-68, and 83-84 under 35 USC 103(a) over JP04345828 (JP'828)**

Applicants requested a professional translation of JP'828 and a copy (JP1992-345828(A)) was forwarded to the USPTO and therefore is of record.

Appellants' claim 1 recites as follows.

1. A multilayer film or sheet comprising:
a.) a first co-extruded polymeric layer consisting essentially of an ionomer and a first additive; and
b.) a second co-extruded polymeric layer consisting of an ionomer and a second additive;
wherein the film or sheet is a thermoformable film or sheet having a thickness in the range of from about 8 mils to about 60 mils; the first co-extruded polymeric layer is surface layer; the second co-extruded layer is in contact with said first co-extruded polymeric layer; and the first or second additive is one or more UV stabilizer, UV absorber, antioxidant, thermal stabilizer, anti-stat additive, processing aid, fiber glass, mineral filler, anti-slip agent, plasticizer, nucleating agent, pigment, dye, flake, or mixtures thereof.

JP'828 discloses on page 1 in the bracket [structure] as follows.

> The multilayer film is comprised of first outer layer 1, which is selected from a group made of EVA, VLDPE and a mixture thereof, core or inner layer 2, which is made of an ionomer or a mixture of said ionomer and EVA, EMAA or EAA, second outer layer 3, which is selected from a group made of EMAA, EAA and an ionomer. As for the manufacturing method, the above described three layers are simultaneously extruded as a multilayer film precursor laminate and then the obtained multilayer film precursor laminate is elongated by a racking or/and blowing method thereby obtaining a desired film thickness.

*See also*, claims 1, 46, and 55 and paragraph [0009].

First, in claims 15 and 40, JP'828 expressly discloses that the second outer layer c is a sealing layer, which comes in contact with a product packaged by said film. Similar disclosure is found in paragraph [0013]. Such disclosures demonstrate that the second outer layer cannot be a surface layer which, according to appellants' specification, is an outside layer that is "skin" layer or decorative. *See. e.g.*, page 5, lines 6-23 (. . . thermoplastic sheet (skin) for surfacing polymer parts . . . the decorative sheet involve both extruded monolayer and multilayer sheeting, . . . blend top surface layer co-extruded onto a selected second polymer layer . . . the decorative skin sheet

on the outer surface thereof). There are numerous disclosures in appellants' specification indicating that the surface layer is the "face" or outside layer.

To the contrary, the second outer layer disclosed in JP'828 is for sealing layer meaning it is "sticky" at right temperature for sealing with another film or sheet or oterh subject and therefore cannot be a surface or face layer.

Indeed the outer or 'face' layer of JP'828 disclosed in [0033] as layer (a) is preferably an outer surface layer which does not come in contact with a product when said film is used. Layer (a) is selected from a group of EVA, VLDPE and a mixture thereof (claim 1). Therefore it is clear that the outer 'face' layer of JP 828 is not an ionomer layer.

Secondly, appellants' claims call for a thermoformable film or sheet. To the contrary, JP'828 does not suggest a thermoformable film or sheet.

The purpose (JP'828) is to provide a multilayer film excellent in shrinkage and resistance against rough use and used as a container or package. JP'828, page 1, in the bracket [objective]. JP'828 discloses a process of making the multilayer sheet with a heat-shrinkable property where [0021] the precursor laminate is heated until it reaches the softening point, then said laminate is elongated by blowing vertical bubbles, the resultant thin laminate film is cooled, the bubbles acre crushed in a spreading roller and the obtained film is wrapped around a roller with tension. This is an orientation process such as described in the Encyclopedia of Polymer Science & Technology, see pages 563-565 of volume 2 (attached hereto as ATTACHMENT I). This is distinctly different from thermoforming process, also described in the Encyclopedia of Polymer Science & Technology (attached hereto as ATTACHMENT II).

A thermoformable film or sheet is patentably distinct from a heat shrinkable film.

In Paleari (US5622780, listed in an IDS applicants previously submitted on 09/05/2006; of record), both heat shrinkable film and thermoformable film are defined. There, a heat shrinkable film is defined as "oriented film which ***shrinks*** by at least 10% in at least one direction at 85°C" (column 2, lines 49-51). A thermoformable film is defined as a "film suitable to be used in a vacuum or compressed air forming or plug assist vacuum or compressed air forming method. ... the term 'thermoformable film' is intended to refer to a ***rigid*** thermoformable sheet which is thermoformed by the above conventional methods" (column 2, line 57 to column 4, line 18). One skilled in the art is aware that a packaging film cannot be rigid.

Application No.: 09/833452
Docket No.: AD6728USNA

The two film types are further distinguished in Paleari (heat shrinkable films disclosed in column 7, line 38 to column 8, lines 36 and thermoformable films disclosed in column 8 lines 37-59).

Based on Paleari disclosure, applicants' claims, reciting thermoformable film or sheet, are not obvious over the JP'828 disclosure, which does not suggest a thermoformable film or sheet.

Also submitted on 09/05/2006 is Lustig (US4863784; of record), which discloses a coextruded heat shrinkable multilayer film for packaging fresh red meat. To be heat shrinkabe, "the film must be biaxially stretched in order to produce shrinkage characteristics sufficient for the film to heat shrink within a specified range of percentages, e.g., from about 15 to 60% at about 90°C" (column 2, lines 35-40)/

Thirdly, a packaging film such as disclosed in JP'828 is clear and see-through for packaging food such as, for example, meat to allow consumers to clearly identify the food packaged therein. Therefore, JP'828 cannot and does not suggest that an additive such as pigment be included in one or more layers of the film.

Claim 6 and its dependent claims further distinguish over JP'828 in reciting first co-extruded layer being clear and second co-extruded polymeric layer comprises the polymer and an additive selected from pigment, dye, flake, or mixtures thereof.

Claim 43 further distinguishes over JP'828 in reciting that the film is adhered to a substrate. JP'828 does not suggest a thermoformable film adhered to a substrate.

Claims 66-68 further distinguish over JP'828 in reciting the ionomer in reciting that the first co-extruded polymeric layer and the ionomer in the second co-extruded polymeric layer must have flow properties to allow the ionomer in the first co-extruded layer and the ionomer in the second co-extruded polymeric layer, when co-extruded, to flow to the full width of the die.

Claims 69-72 further distinguish over JP'828 in reciting the ionomer in reciting DOI of at least 80 and a gloss that exceeds 60% at a 20 degree angle.

Claim 82 further distinguishes over JP'828 in reciting that the substrate is metal, polymer, or polymer composite.

Claim 83 further distinguishes over JP'828 in reciting that the substrate is metal, polymer, or polymer composite and the multilayer film or sheet is clear.

Application No.: 09/833452
Docket No.: AD6728USNA

The 103 analysis also requires that the invention be considered as a whole. JP'828 is directed to a packaging film which is not require the characteristics of a decorative surface.

**Rejection of claims 1, 3, 6, 43, 54-55, 57-63 (should be 60), 66-68, and 83-84 under 35 USC 103(a) over Flieger (US5789048)**

Appellants' claim 1 recites as follows.

1. A multilayer film or sheet comprising:
a.) a first co-extruded polymeric layer consisting essentially of an ionomer and a first additive; and
b.) a second co-extruded polymeric layer consisting of an ionomer and a second additive;
wherein the film or sheet is a thermoformable film or sheet having a thickness in the range of from about 8 mils to about 60 mils; the first co-extruded polymeric layer is surface layer; the second co-extruded layer is in contact with said first co-extruded polymeric layer; and the first or second additive is one or more UV stabilizer, UV absorber, antioxidant, thermal stabilizer, anti-stat additive, processing aid, fiber glass, mineral filler, anti-slip agent, plasticizer, nucleating agent, pigment, dye, flake, or mixtures thereof.

First, Flieger dose not disclose or suggest a thermoformable film.

Secondly, the examiner rejected the claims because Flieger discloses that thickness of 70-125 microns "should be" enough for a 25 Kg bag. However, the 25 kg bag is the only bag contemplated in Flieger because it expressly discloses, column 1, lines 16-30, that a 25 kg bag is the bag typically used in the packaging polymeric products and elastomer and a heavy duty bag is required for such packaging. No heavier bags are required. Flieger therefore discloses the heavy duty bag as having 70-125 microns thick, nothing other than this thickness is implied because, from the four corners of Flieger disclosure, it does not appear that Flieger suggests that any thicker film is needed. Therefore, Flieger cannot suggest the thickness recited in applicants' claims.

Thirdly, the objective of the invention disclosed in Flieger is to provide a consumable package (the 25 kg bag) that can be processed together with the product it contains (the polymeric products and elastomers). However, the bag itself is essentially a contaminant in the product, so that it is important that the amount of the bag itself is "small in the final product; thus, there is minimal if any effect on the properties of the final product" (column 3, lines 9-11; underline added). Such disclosure is further expanded in column 3 lines 43-47 (As a result, there is no disposal problem for the bag which will melt under normal mixing temperature (90°-95°) and be incorporated fully into the compound giving negligible effect on the subsequent properties of the compound). Flieger discloses

Application No.: 09/833452
Docket No.: AD6728USNA

the bag as heavy duty bag having 70-125 microns thick. Any heavier gauge would increase the amount of the bag in the product and will lead to non-negligible effects on the compound properties.

Indeed Flieger disclosure teaches away from a heavier gauge, and, therefore, cannot suggest the thickness of 8-60 mils of applicants' claims.

Fourthly, the examiner would agree that a very large number of literatures, including patents, disclose multilayer polymer films for packaging foodstuffs and materials. In many, if not all, of the materials, there is usually some need for printing and color (in order that the package can be recognizable to the consumer, contain product and advertising information, distinguish the product brand from the competitor, etc). There is also some need for ultraviolet protection, if the bags are stored in daylight or artificial light. Therefore, there will be many cases of UV additives, color additives etc. Flieger may disclose white pigments and black pigments in the inner layers for UV protection in a bag to contain polymers and elastomers but this may not lead to any obviousness for applicants' claims that deal with a thermoformable film for adhering to a thick substrate. Though this is not in the claims, but the invention should be considered as a whole. Flieger discloses a packaging film, which is not require the characteristics of a decorative surface, whereas applicants' claims are directed to thermoformable film.

Fifthly, pursuant to MPEP 2126.01, which provides that the date of the patent is available as a reference is generally *the date that the patent becomes enforceable* (*italics* applicants'). The date the Flieger patent became enforceable on August 4, 1998.

MPEP 2141.01 provides that . . . an obviousness rejection based on a publication which would be applied under 102(a) if it anticipates the claims can be overcome by *swearing behind the publication date* of the reference by filing an affidavit or declaration under 37 CFR 1.131 (*italics* applicants').

Pursuant to these MPEP guidelines, co-inventor Lori Pike's Rule 131 declaration sworn behind that the invention was conceived and reduced to practice before the critical date of August 4, 1998 (Flieger patent date).

According to MPEP 2126.01, Flieger cannot be a reference.

Claim 6 and its dependent claims further distinguish over Flieger in reciting first co-extruded layer being clear and second co-extruded polymeric layer comprises the

polymer and an additive selected from pigment, dye, flake, or mixtures thereof. Flieger, as the examiner noted, the inner layer is pigmented (black).

Claim 43 further distinguishes over Flieger in reciting that the film is adhered to a substrate.

Claims 57-60 further distinguish over Flieger in reciting film or sheet thicker than 8 mils.

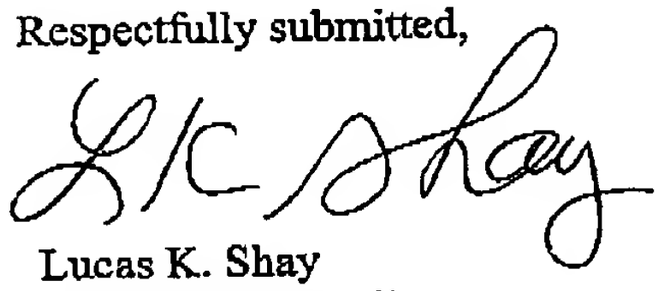
Claims 66-68 further distinguish over Flieger in reciting the ionomer in reciting that the first co-extruded polymeric layer and the ionomer in the second co-extruded polymeric layer must have flow properties to allow the ionomer in the first co-extruded layer and the ionomer in the second co-extruded polymeric layer, when co-extruded, to flow to the full width of the die.

Claims 69-72 further distinguish over Flieger in reciting the ionomer in reciting DOI of at least 80 and a gloss that exceeds 60% at a 20 degree angle. As theexaminer noted, packaging film does not require DOI or glossy surface.

Claim 82 further distinguishes over Flieger in reciting that the substrate is metal, polymer, or polymer composite.

Claim 83 further distinguishes over Flieger in reciting that the substrate is metal, polymer, or polymer composite and the multilayer film or sheet is clear.

Respectfully submitted,



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Application No.: 09/833452
Docket No.: AD6728USNA

ATTACHEMNT I

FILMS, ORIENTATION; Encyclopedia of Polymer Science & Technology, Vol. 2, pages 563-565.

ATTACHEMNT II

THERMOFORMING; Encyclopedia of Polymer Science & Technology, Vol. 8, Pages 222-251.

ATTACHEMNT I



bath must be adjusted with care. Continually circulating the water will increase the effectiveness of the quench. High pressure water jets can help keep pressure on the web against the chill wheel. These jets can also deform the surface of the cast web. If they are at the wrong angle, the web could be pulled away from the chill wheel, reducing the quench rate. If this technique is used, the chill wheel needs to be dried off by the time it rotates to the point where melt is again placed on it. If it is too wet, steam bubbles may form creating serious nonuniformities in the cast web. A nip roll or air knife has been used to accomplish the drying of the roll. Combination of both may be required in high speed operations.

When extruding a tube through an annular die there are two kinds of orientation processes available, blown film process and tubular film process. Blown film conducts the orientation in the melt state. The tube is rapidly pulled away from the die by a nip at the top of a tower. Air is pumped through the annular die to inflate the tube and to provide additional cooling. The molecular orientation produced in blown film is quite low compared to solid-state orientation. The molecules are above their melt and have very fast relaxation times. One often refers to the frost line in a blown film process. This is the point where the melt crystallizes. The polymeric web goes through a clear to hazy transition at this point. Further molecular orientation in the web in this stage of the process typically does not occur.

In the tubular film process, or double bubble process, the extruded tube encompasses a cooled mandrel and is pulled away by a nip (Fig. 3). The mandrel should not impart scratches in the tube. This first "bubble" is usually quenched as rapidly as possible for the same reasons in flat film. Controlling the air pressure inside the first bubble is another handle used to determine the quench rate. A water bath on the outside of the tube provides additional cooling of the extrudate. Water flow around the tube is very important. Too great an impingement against the melt may result in surface defects. A tube quenched in this manner will allow subsequent orientation to occur in the solid state at significantly lower temperatures, resulting in higher molecular orientation.

## Melt-State Orientation—Blown Film

The blown film process, as shown in Figure 4, orients the molecules while they are in the melt state. Inflating the melt bubble provides the orientation. The air pressure in the bubble is maintained to achieve a certain "blow up ratio," the ratio of bubble diameter to the die diameter. The strain rates are relatively low and relaxation times are very fast. The subsequent molecular orientation obtained via this process falls between the high levels of orientation obtained by stretching in the solid state and very low levels obtained in standard casting operations. The orientation occurs during elongational flow of the melt. Although elongational flow is much more effective at orientation than shear flow, this process has limitations.

There are many methods to increase the amount of orientation frozen in during the blown film process. Systems have been developed to approach

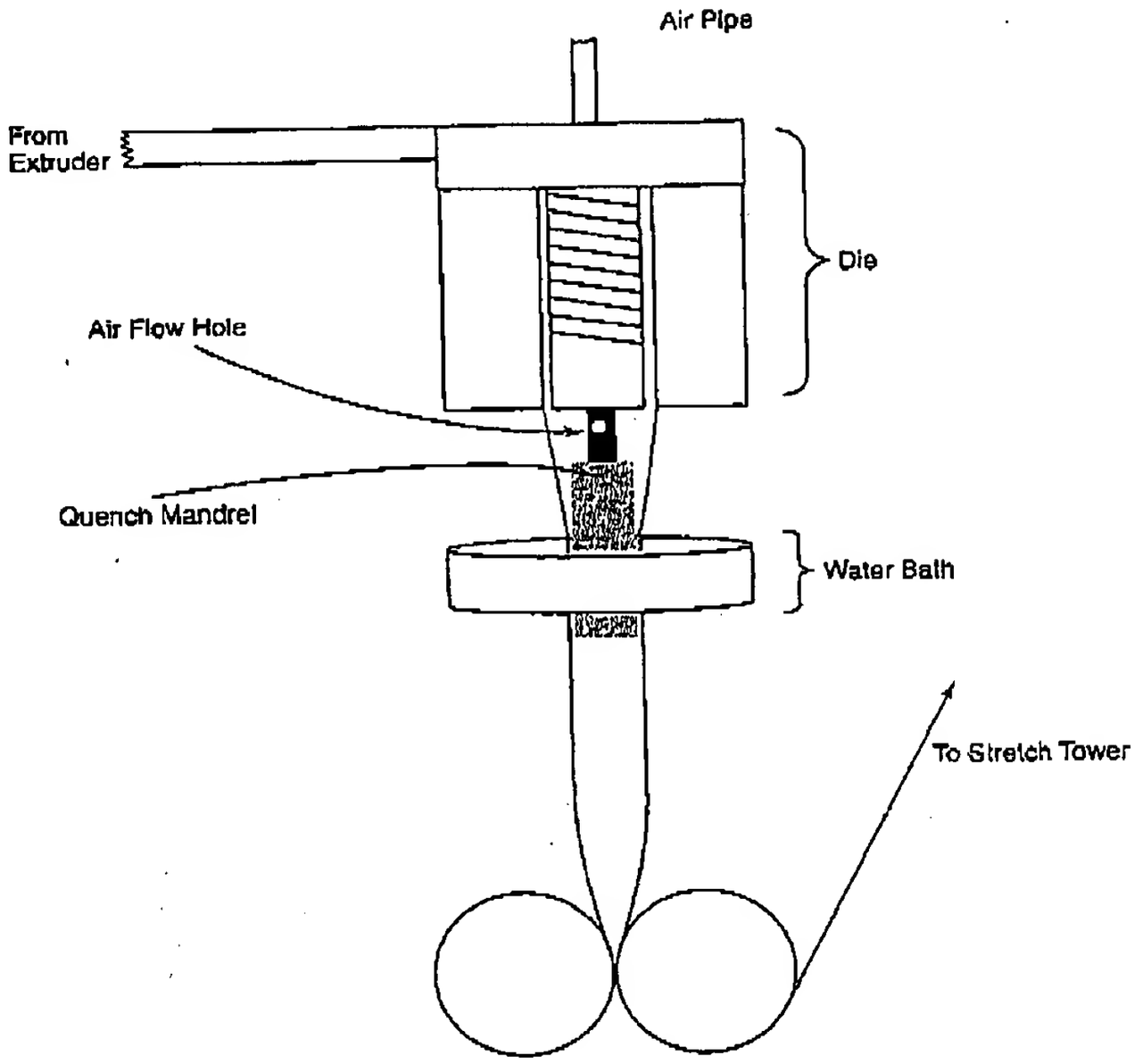


**Fig. 3.** Tubular film quenching.

quenching a blown film tube from both internal to the bubble and external to the bubble. The faster the quench, the greater molecular orientation is obtained. Internal devices (2,3) can cool the film preferentially, locking in molecular orientation. Externally cooling the blown film bubble in multiple stages (4–6) will allow greater orientation to occur in the tube. Operation of the primary air cooling ring has a dramatic impact on final properties (7). Attempts to separate the machine direction stretching from the transverse direction have shown some promise (8).

Choice of materials, as in any process, is a major consideration. Most resin suppliers and equipment vendors have laboratory to pilot-scale equipment that can screen various resins. Blends of similar resins can also be useful in obtaining greater orientation in the blown film process (9).

There been attempts to generate off-axis orientation in blown film. Rotation of some component of the annular die may impart diagonal orientation (10,11).

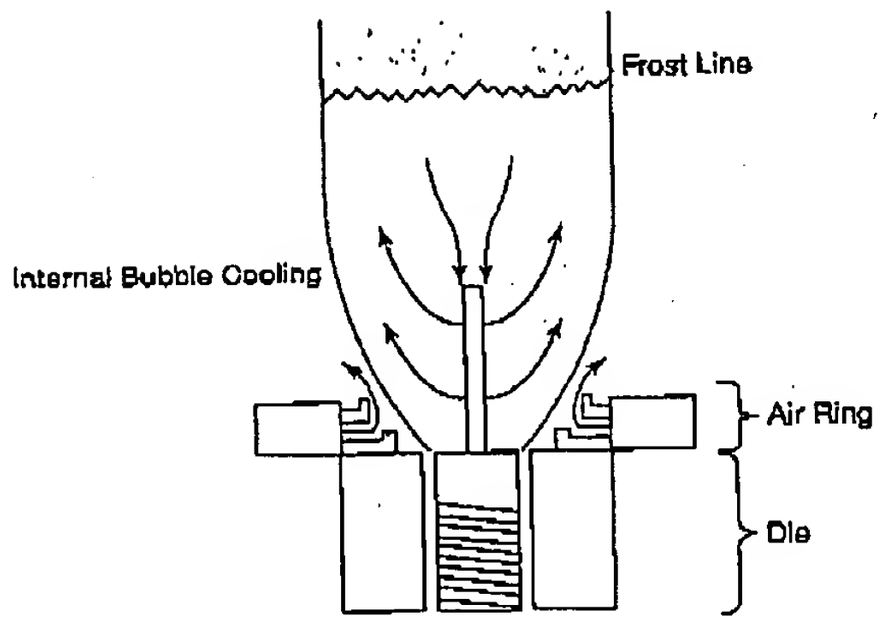


**Fig. 4.** Blown film process, quench air ring, and internal bubble cooling.

## Solid-State Orientation—Monoaxial Orientation

**Machine Direction.** There are applications in which improvements in properties are required in only one direction. Most often, this high strength axis is in the machine direction (12). Equipment that stretches a film in the machine direction can be called machine direction orienter or length orienter. Uniform heating of the unoriented web is achieved by wrapping the web around a series of heated rolls. These preheat rolls need to have very smooth surfaces to ensure good heat transfer to the web and to prevent scratching the film. These rolls may be driven rolls or idler rolls. Another method to heat up the web uses ir radiation (13). It is also possible to immerse the cast web in a temperature-controlled bath to bring it up to temperature prior to orientation (14).

For a crystallized semicrystalline polymer, the web is heated to below, but near, the melting point. Amorphous polymers will only need to be heated to slightly above their glass-transition temperatures ($T_g$).

The web passes through an inlet nip, over the preheat rolls and enters the stretch section (Fig. 5). A high speed nip pulls the film in the machine direction. The amount of orientation in the film will be determined by the strain rate, stretch temperature, amount of stretch, and how quickly the film is cooled. Stretching between two rolls is a very high strain rate process in industrial settings, often of the order of 5000%/s. The level of orientation attainable is quite high.

Selection of the polymeric material plays an important role in the efficiency of this process. One needs to consider the molecular weight, the molecular weight distribution, and even the additive package. High loadings of some stabilizers may plate out on the equipment and interfere with consistent heat transfer.

Subsequently, a second or even more (15) machine direction stretching stations may be used. The web may have to be further heated before it is stretched a second time. This process can produce higher molecular orientation in films than

ATTACHEMNT II



# THERMOFORMING

## Introduction

*Thermoforming* is the art and science of forming commercial products by heating plastic sheet to a softened, pliable state, pressing the sheet against a cool mold, holding the formed sheet against the mold until rigid, and trimming the formed part from the web or skeleton surrounding it. Nearly all unfilled or unreinforced thermoplastics are formed in this manner on conventional equipment. Newer forming technologies are used to form filled and reinforced thermoplastics and certain thermosetting polymers. In general, thermoforming is used when large surface area-to-wall thickness parts are needed, when rapid evaluation of product designs are sought, when very high production rates of thin-walled parts are desired, and when a few to a few hundred thick-walled parts are needed.

Although commercial thermoforming, sometimes called *vacuum forming* or *swedging*, was not developed until the 1870s, when cellulose nitrate was first cut into thin sheets, Egyptians, Pacific natives, and American Inuits formed naturally occurring tortoise sheet and tree bark or natural cellulose into bowls and boats long before then (1).

In the 1870s, cellulose sheet was formed using metal molds and steam as the heating and forming medium (2,3). The earliest products were baby rattles, toys, mirror cases, and hairbrush backs. In the early 1900s, piano keys were drape-formed over captive wooden cores. In 1930, Fernplas Corp. patented a bottle fabricated from two thermoformed halves. Relief maps for the U.S. Coast and Geodetic Survey were thermoformed of cellulose acetate in the 1930s. The first automatic roll-fed thermoformer was sold by Clauss B. Strauch Co., in 1938, to manufacture cigarette tips and ice-cube trays. The heating, bending, and shaping of plastic sheet were taught in high school industrial art courses in the late 1930s (4).

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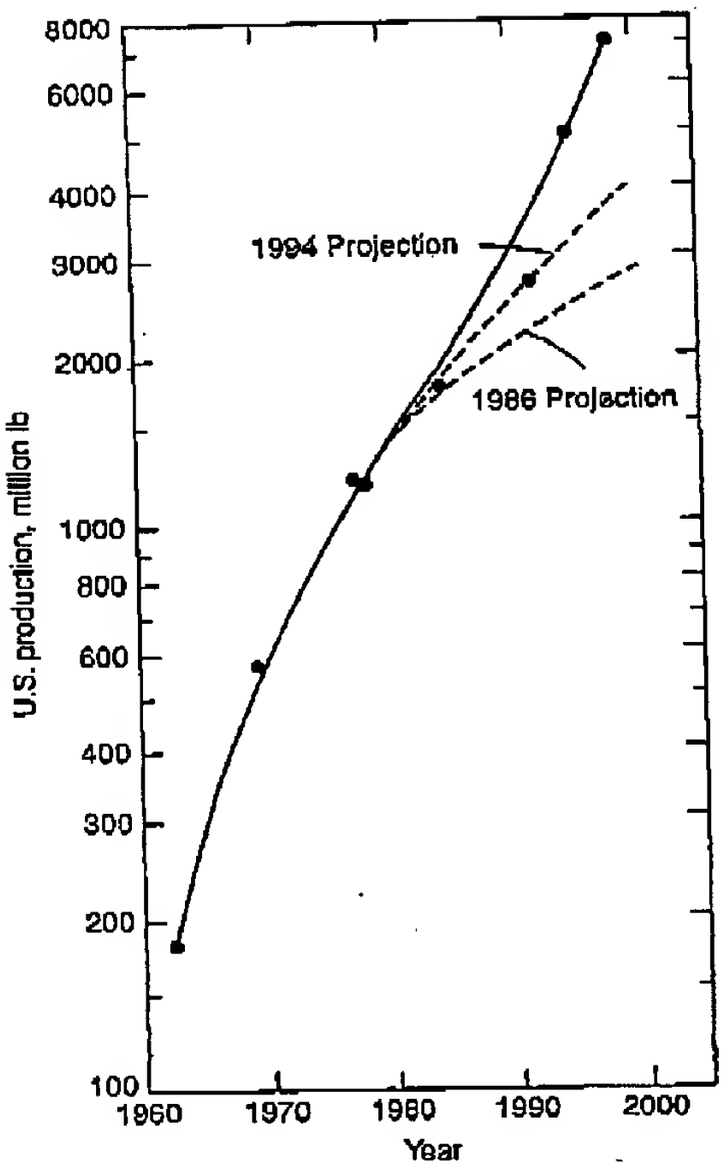


**Fig. 1.** Thermoforming production in the United States (7). 1 million lb = 455,000 t. Redrawn and used with permission of Hanser Publications.

The Second World War accelerated interest in thermoforming, with the demand for cast poly(methyl methacrylate) fighter/bomber windows, gun closure and windscreens (5).

By the mid-1950s, thermoformed blister packages and food containers of polystyrene were found in most grocery stores. In 1962, approximately 77,000 t of plastic was thermoformed in the United States. By 1998, approximately 2.9 million metric tons of plastic were thermoformed in North America (6) (Fig. 1). This is a sustained annual growth rate of about 10% over nearly four decades. An additional 4.55 million metric tons are thermoformed worldwide. The total world market is estimated to have a value of about US$ 35,000 million.

Thermoforming is typically bifurcated into thin-gauge thermoforming and heavy- or thick-gauge thermoforming. As seen in Table 1, thin-gauge thermoforming uses sheet 1.5 mm or less in thickness, with its primary products being packaging containers. Typical disposable products include blister packages, point-of-purchase containers, bubble packages, slip sleeve containers, auto/video

NOV. 13. 2007 1:36PM NO. 9183 P. 18



Table 1. Thermoforming Categorization[a]

| Item | Thin-gauge | Heavy-gauge |
|---|---|---|
| Sheet thickness range | Less than 1.5 mm | Greater than 3.0 mm |
| Dominant products | Packaging, disposables | Cabinetry, industrial |
| Sheet handling | Rolls | Palletized cut sheet |
| Typical machine type | In-line former, trimmer | Shuttle or rotary press |
| Press size | To 0.8 × 2 m | To 4 × 6 m or more |
| Machine control aspects | Automated | Automated to manual |
| Controlling aspect, heating | Heater output | Conduction into sheet |
| Heater type | Electric, ceramic, quartz | Electric, catalytic gas, forced hot air |
| Pattern heating | Not usually done | Common |
| Part size tendency | Small | Medium to very large |
| Number of mold cavities | Many to a hundred | One or two, usually |
| Mechanical assist | Plug | Plug, billow, vacuum box |
| Mold type | Female, usually | Male, female, mixed |
| Mold materials | Aluminum, machined | Wood, plaster, syntactic foam, white metal, cast aluminum |
| Mold cooling | Active, controlled | Active to none for prototype |
| Free surface cooling | Ambient, usually | Forced air, fogging |
| Trimming aspects | Punch and die, rim roll | Multiaxis routing |
| Nonproduct trim level | About 50% | About 25–30% |
| Wall thickness tolerance, normal | 20% | 20% |
| Wall thickness tolerance, tight | 10% | 10% |
| Pressure forming application | Deep draw, formed rim | Textured surfaces, deep draw |

[a]Ref. 8.

cassette cases, hand and power tool cases, cosmetic cases, meat and poultry containers, unit serving containers, convertible-oven food serving trays, wide-mouth jars, vending machine hot and cold drink cups, egg cartons, produce and wine bottle separators, medicinal unit dose portion containers, and form, fill, and seal (FFS) containers for foodstuffs, hardware supplies, medicine, and medicinal supplies.

Heavy-gauge thermoforming uses sheet 3 mm or more in thickness, with primary products being permanent or industrial products. Typical products include equipment cabinets for medical and electronic equipment, tote bins, single and double deck pallets, transport trays, automotive inner-liners, headliners, shelves, instrument panel skins, aircraft cabin wall panels, overhead compartment doors, snowmobile and motorcycle shrouds, fairings and windshields, marine seating, locaters and windshields, golf cart, tractor, and RV shrouds, skylights, shutters, bath and tub surrounds, lavys, single- and double-wall shipping containers and pallets, storage modules, exterior signs, swimming and wading pools, landscaping pond shells, luggage, gun and gulf club cases, boat hulls, animal carriers, and seating of all types.

There is a growing but very still limited market for products formed from sheet between about 1.5 mm (thin-gauge) and 3.0 mm (heavy-gauge) thickness. Usually, products of this thickness are either too expensive to be disposable or too thin to be industrial or permanent products. One major application is in the manufacturing of very large volume drink cups (1/2 L or more).

PAGE 18/45 * RCVD AT 11/13/2007 1:35:16 PM [Eastern Standard Time] * SVR:USPTO-EFXRF-1/4 * DNIS:2738300 * CSID:302 992 3257 * DURATION (mm-ss):13-50

Currently thin-gauge thermoforming accounts for about three-quarters of all sheet formed, in both tonnage and dollar volume. Thin-gauge thermoforming companies tend to be very large with broad spectra of products. Furthermore, companies that manufacture products may also do in-house thin-gauge thermoforming for the packages for these products. Heavy-gauge thermoforming companies tend to be small with narrow product lines. As a result, there are many more heavy-gauge thermoforming companies than thin-gauge thermoforming companies. In 2001, it was estimated that there were about 500 heavy-gauge thermoforming companies and less than 200 thin-gauge thermoforming companies in North America (9).

As outlined in Table 1, there are substantial differences in the characteristics of these two thermoforming categories. In addition to the sheet thickness criterion, there is a difference in the way the sheet is presented to the thermoforming machine. Thin sheet is usually delivered in rolls of up to 3000 m in length, weighing up to 2300 kg and having diameters up to 1.5 m. The sheet is fed continuously into the thermoforming machines that are usually called roll-fed machines. Thick sheet is usually guillotine-cut to size and palletized. The individual sheets are then loaded manually or pneumatically into the thermoforming machines, known as cut-sheet machines.

Thermoforming is a competitive technology. In thin-gauge it competes with paper, paperboard, plastic-coated paper and paperboard, paper pulp, expanded polystyrene foam, aluminum foil, and roll-sheet steel. It also competes with plastics extrusion, compression molding, stretch-blow molding, injection molding, and injection-blow molding. In heavy-gauge, it competes with injection molding, rotational molding, blow molding, fiberglass-reinforced polyester resin spray-up molding and lay-up molding, compression molding, sheet compound molding, bulk compound molding, sheet metal forming, and metal die casting.

When compared to other technologies, thermoforming offers many advantages: there is a wide variety of polymers from which to choose; molds are single-sided and are thus less expensive than injection molds; the time from concept to final part acceptance is usually quite short; there are many available mold materials; aluminum—the mold material of choice—is lightweight, has a high thermal conductivity, is relatively inexpensive, and is easy to machine and cast; processing temperatures are low; processing pressures are very low; mold detail replication is good; part surface area-to-wall thickness is extremely high; and there are many excellent trimming techniques (10).

However, thermoforming has some serious limitations. Among others, the polymer of choice may not be extrudable or may sag too much during heating in the thermoforming machine; there is additional cost in producing sheet; the unused portion of the sheet—the trim, web, or skeleton—must be recycled to keep sheet costs reasonable; because of the end-use of the product (medical, pharmaceutical, foodstuffs), recycling of the trim may not be acceptable, it may not be possible to stretch the sheet sufficiently to achieve the desired part shape, part wall thickness is not well-controlled or predictable, and is not uniform across the part; wall thickness cannot be changed locally through design; surface texture may be required on both sides of the part; the part performance criteria may required reinforced or highly filled polymers; the part tolerance, edge radii, and draft angles may be unacceptably tight for the thermoforming process; and there

may be other processes that are more economically attractive. A general comparison of four thermoplastic processes is given in Table 2 (see INJECTION MOLDING; BLOW MOLDING).

## Machinery

The specific details of thermoforming machinery depend on whether thin-gauge or heavy-gauge parts are fabricated. However, all machines include some form of sheet handling device, some way of moving the sheet from one station to another, a sheet heating oven, a vacuum system, a forming press containing the mold assembly, a formed part removal region, and a system for controlling the various elements of the machine that allow sheet transfer from one station to another. In addition, the machines may include some form of sheet prestretching, such as a preblowing step or mechanical pushers or plugs, a pressure system, a mold cooling system, a trimming press, and some form of trim removal.

**Thin-Gauge Machines.** The schematic in Figure 2 illustrates the most common thin-gauge thermoforming machine arrangement. The sheet, delivered as a roll, is indexed through the machine on pins that are arranged along parallel or near-parallel lengths of continuous link chains. The sheet is usually uniformly heated from both top and bottom with infrared heaters. Most commercial machines use ceramic bricks or tiles, metal plate heaters, metal rod heaters, quartz tubes, or quartz plate heaters as energy sources. Typically, the ovens accommodate two or more "shots" or forming stops. Once the sheet is at the forming temperature, it is indexed into the forming press. The forming press contains at least one platen with the desired mold assembly. If the parts being formed require matched forming, as is the case with low density foam sheet, a second platen contains the matching mold assembly. If not, the second platen may contain a pressure box, a

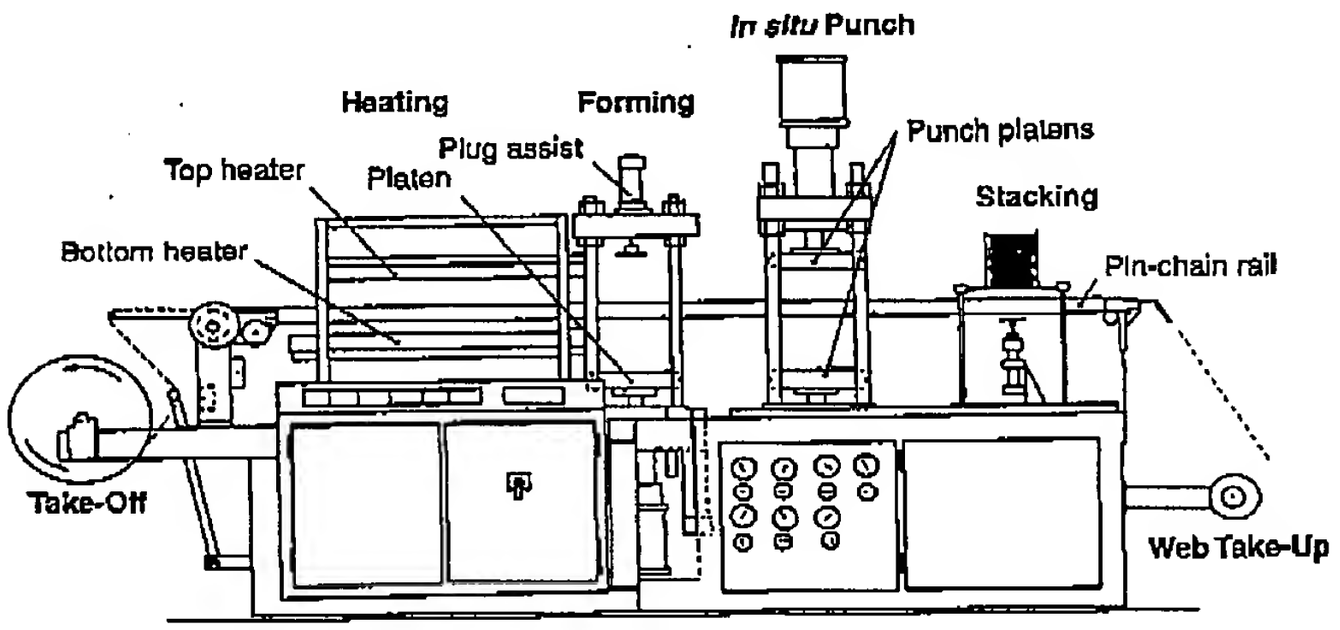


Fig. 2. Schematic of small thin-gauge thermoforming machine (Kiefel GmbH, Freilassing, Germany). Used with permission of Hanser Publications.

PAGE 21/45 * RCVD AT 11/13/2007 1:35:16 PM [Eastern Standard Time] * SVR:USPTO-EFXRF-1/4 * DNIS:2738300 * CSID:302 992 3257 * DURATION (mm-ss):13-50

NOV. 13. 2007 1:37PM



**Table 2. Comparison of Four Thermoplastic Processes[a]**

| Characteristic | Thermoforming | Injection molding | Blow molding | Rotational molding |
|---|---|---|---|---|
| Polymer form | Sheet | Pellets | Pellets | Powder |
| Variety of polymer | Good to excellent | Excellent | Good | Fair to limited |
| Raw material cost | Polymer + sheet extrusion | Standard | Standard | Polymer + grinding |
| Variety of mold materials | Very many | Very limited | Limited | Many |
| Mold cost | Moderate to low | Highest | High | Moderate to low |
| Production mold material | Aluminum | Steel | Aluminum | Aluminum, steel |
| Thermal cycling of mold | Gentle | Moderate | Moderate | Severe |
| Process key | Rubbery solid sheet | Viscoelastic liquid | Elastic liquid | Melting Powder |
| Cycle time | Moderate to short | Very short | Moderate | Very long |
| Man/machine interaction | Normally high | Nil to low | Low | Very high |
| Part wall uniformity | Fair to poor | Excellent | Poor to fair | Good to excellent |
| Major design problems | 3D corner, wall thickness uniformity | Gating, weld line | Pinch-off, wall uniformity | Porosity |
| Part failure mode | Thin corners, microcracks | Weld line | Thin side walls, poor pinch-off | Poor tensile strength |
| Operating pressure, MPa[b] | ~0.1 to 0.5 | 10 to 100 | 0.5 to 2.5 | 0 to 0.1 |
| Operating temperature, °C | 50 to 250 | 150 to 300 | 100 to 250 | 200 to 350 |
| Filling methods | Manual to automatic | Automatic | Automatic | Manual |
| Part removal methods | Manual to automatic | Automatic | Automatic | Manual |
| Flash, trim | Highest | Low to nil | Moderate to high | Moderate to low |
| Inserts | Possible | Feasible | Feasible | Usual |
| Orientation in part | Highest | Moderate to high | High to moderate | Unoriented |
| Stress retention | Highest | High | High to very high | None to little |
| Shrinkage, warpage | High to moderate | Controllable | Moderate to high | High |
| Part design advantage | Very thin walls | Wide variation in part wall thickness | Hollow parts | Very large hollow parts |
| Part characteristic | Single-sided | Both sides finished | Single-sided | Single-sided |
| Part surface finish | Good to very good | Excellent | Very good | Good |
| Surface texture | Good | Excellent | Very good | Good to fair |

[a]Ref. 11.

[b]1 MPa equals approximately 10 atm.

NO. 9183 P. 21

mechanical plug assist assembly, and/or a clamping grid assembly. There are several ways of opening and closing the forming press. Mechanical and pneumatic toggles have been used for decades. Electrically driven platens have become quite popular recently.

The majority of thin-gauge parts are formed into female or negative cavities. For deep cavities or multiple-compartmented cavities, mechanical assists, called plugs, are used to prestretch the sheet before vacuum and/or pressure is used to force the sheet against the mold surface. Air pressure to 5 bar is used, in conjunction with vacuum, for deeply drawn parts or for parts requiring high surface detail or sharp radii.

In thin-gauge forming, there are three common ways of removing the formed part from the web, skeleton, or unformed portion of the sheet. In-mold trimming employs steel rule dies that are a portion of the clamping assembly holding the sheet to the mold surface. Once the parts are formed, the steel rule die assembly is activated to cut the parts free of the web. In-machine trimming employs a separate trimming station that is situated downstream of the forming press, but still within the machine frame. The sheet containing the formed parts is indexed from the forming press directly into this trimming station, where steel rule dies separate the parts from the web. In-line trimming employs a separate trimming press that is downstream from the forming machine, as shown in Figure 3 (12). The sheet containing the formed parts is fed from the end of the forming machine pin-chain assembly into a separate indexer on the trimming press. The sheet containing the formed parts passes between a punch assembly and a die assembly. The punch pushes the formed parts against a trim die, cutting the parts away from the web and pushing them onto a collection table.

FFS machines are used in for packaging pharmaceuticals, foodstuffs, and medical supplies. As seen in Figure 4, thermoforming is a small portion of the process (13). In these machines, the sheet is usually pulled through the entire

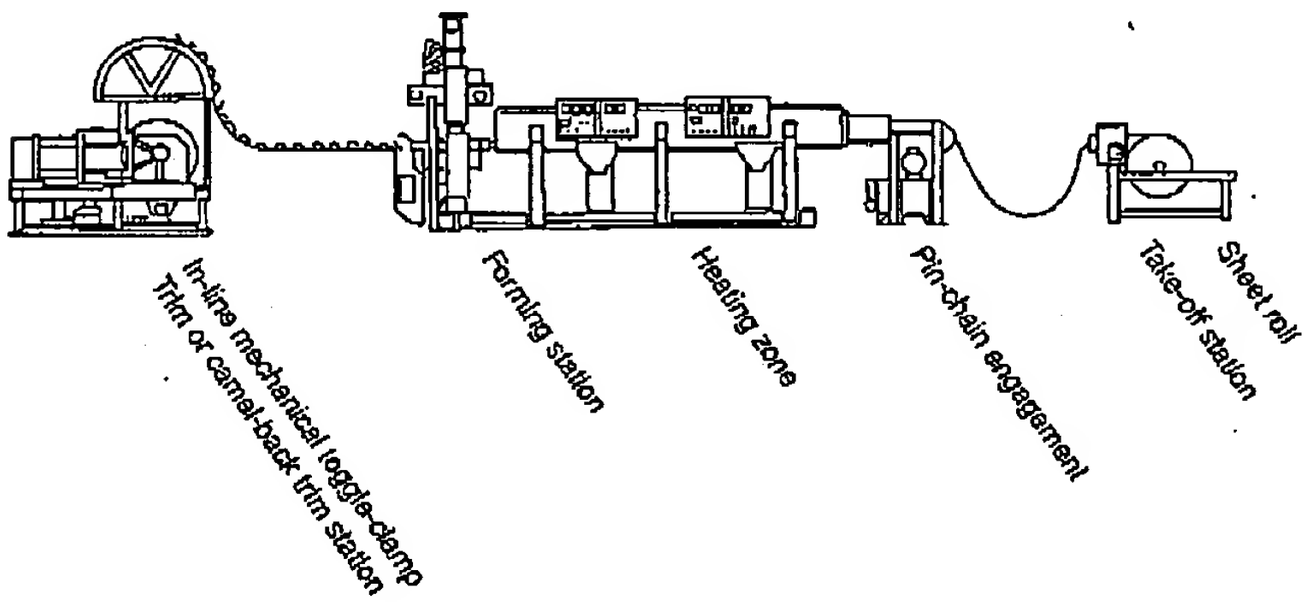


Fig. 3. Schematic of large thin-gauge thermoforming machine (Battenfeld—Glouster, Glouster, Mass.) (12). Used with permission of Hanser Publications.

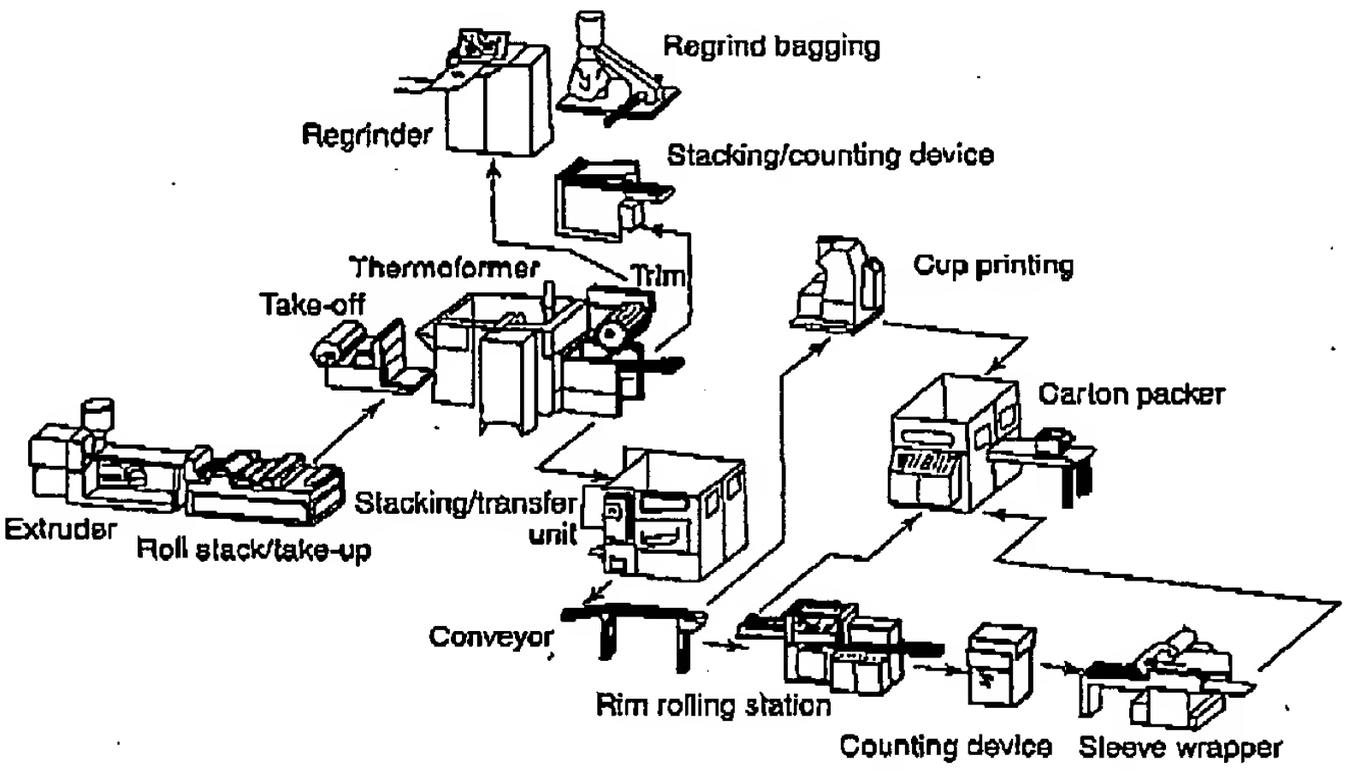


Fig. 4. Thermoforming as an integral part of thin-gauge container production line (13). Used with permission of Hanser Publications.

FFS sequence. The sheet is heated by contact with heated plates or rolls. FFS technology is most effective when the sheet is on the order of 250 $\mu$m or so.

For all roll-fed applications, it is economically necessary to collect the web for regrinding and reprocessing into sheet. For the in-line trimming press, the web is guillotined at the press and the chips are vacuum-collected for reprocessing.

**Heavy-Gauge Machines.** There are several common designs for heavy-gauge thermoforming machines. The simplest and most widely used is the shuttle machine (Fig. 5) (14), where the sheet, cut to size and palletized, is loaded, one

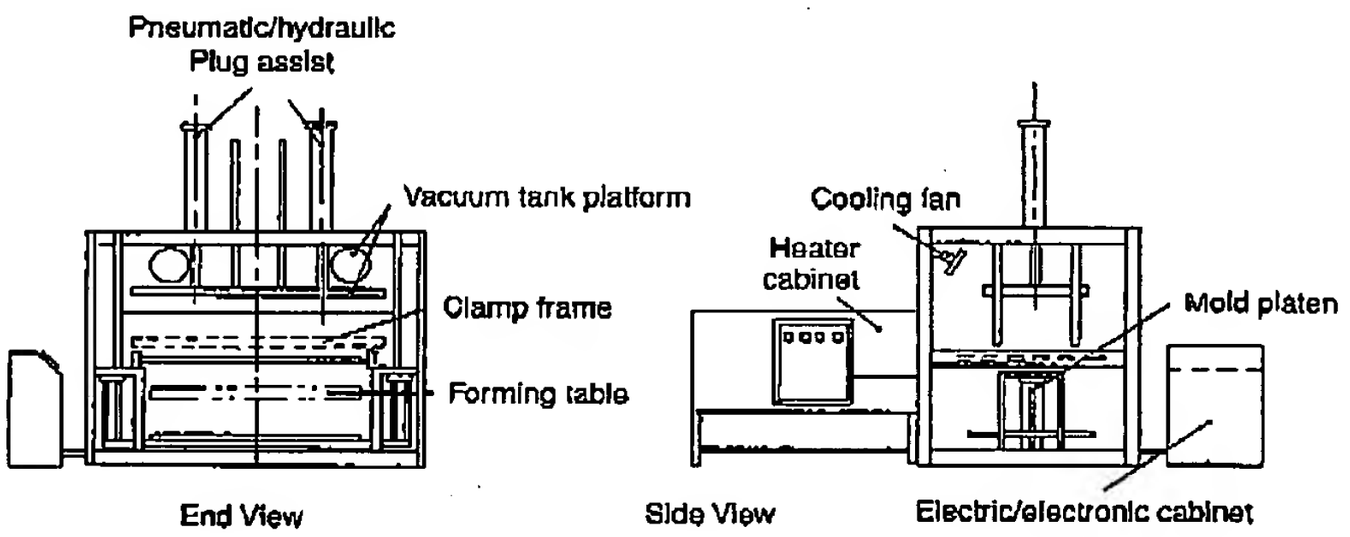


Fig. 5. Schematic of heavy-gauge shuttle thermoforming machine (Drypol/Zimco, no-longer in business) (14). Used with permission of Hanser Publications.

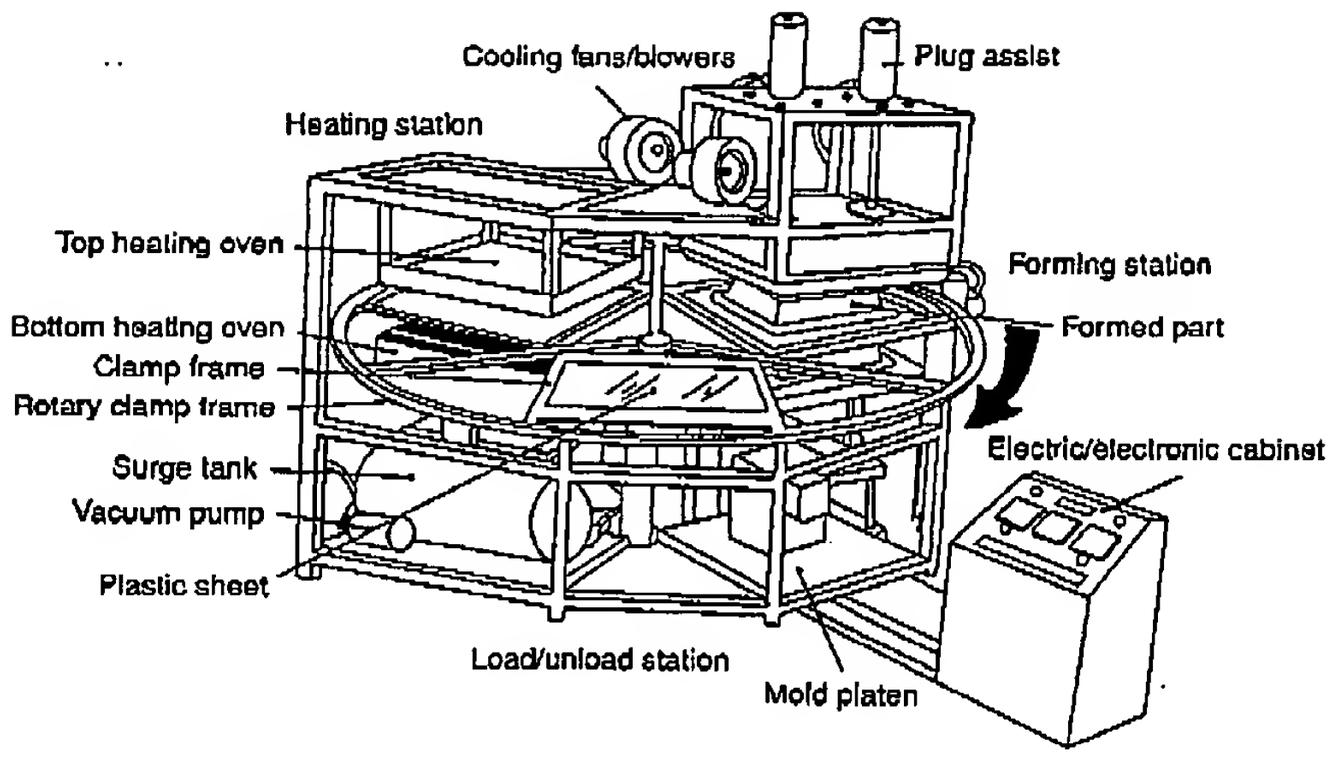


**Fig. 6.** Schematic of heavy-gauge rotary thermoforming machine (15). Used with permission of Hanser Publications.

sheet at a time, in a four-sided clamp frame and shuttled into the oven. When the sheet is at its forming temperature, it is shuttled to the forming press. When the sheet has been formed and cooled, it is removed from the clamp frame to a trimming fixture. Shuttle presses are very versatile and capable of forming parts of nearly unlimited dimensions. Shuttle presses with two forming stations and a central oven are used to overcome the economically inefficient operation of a single forming press machine. Rotary thermoforming machines, with either three or four stations, are quite energy efficient, but require more care in setting up. Figure 6 is a schematic of a three-station rotary machine (15). These machines are also limited in the size of the parts that can be formed.

A three-station machine has one heating station, in addition to the forming station and the load–unload station. The four-station machine has two heating stations. The sheet is usually uniformly heated from both top and bottom with infrared heaters. Most commercial machines use ceramic bricks or tiles, metal plate heaters, metal rod heaters, quartz plate heaters, or catalytic gas heaters as energy sources. As with thin-gauge thermoformers, once the sheet is at the forming temperature, it is indexed into the forming press. The forming press contains at least one platen with the desired mold assembly. The press may contain a second platen. For single-sheet forming, the second platen may contain a pressure box, a mechanical plug assist assembly, and/or a vacuum draw box to pneumatically prestretch the sheet. As with thin-gauge forming, the mold may be mounted on either the top or the bottom platen. The mold frame usually contains one to a few molds, which can be either male or female. Mechanical toggles or electrically driven chain with rack-and-pinion guides are used to raise and lower the platen. If a pressure box is used, the mold sections are mechanically locked and pressure bags are inflated to ensure an intimate seal against air pressures to 0.6 MPa.

Twin-sheet thermoforming is the method of forming hollow or semihollow parts such as pallets and door panels. Four-station machines are commonly used to form these parts. The first sheet is loaded in the clamp frame and rotated into the first oven. After a predetermined time, the second sheet is then loaded in the next clamp frame and rotated into the first oven. This action rotates the first sheet to the second oven. When the first sheet is at its forming temperature, it is rotated to the forming press and formed into the top mold cavity. When the part is sufficiently cooled, the clamp frames release the sheet. This allows the second sheet, in its clamp frame, to be rotated to the forming press, where it is formed into the top mold cavity. Then the platens close, are mechanically locked together, and air is forced under pressure between the two sheets. This forces the sheets against their respective molds and the clamping force provides for sealing of peripheral edges and any mating surfaces designed into the part. The welded-together sheets are then released from the clamp frame and removed to the trimming device (16).

There are many ways to trim the part from the surrounding plastic. Hand-held routers, band saws, and circular saws are commonly used. Hand-held drills are used for holes and slots. Computer numerical-controlled routers are used extensively for parts requiring dimensional accuracy along trim lines.

## Process Characteristics

**The Forming Process.** Drape forming (*male* or *positive forming*; Fig. 7) and vacuum forming (*female* or *negative forming*; Fig. 8) are the earliest and simplest methods of thermoforming (17). Both methods yield parts with very nonuniform wall thicknesses. Free forming (*billow* or *free bubble forming*) uses no mold. The sheet is simply pneumatically stretched to the desired extent, and then allowed to cool in this shape.

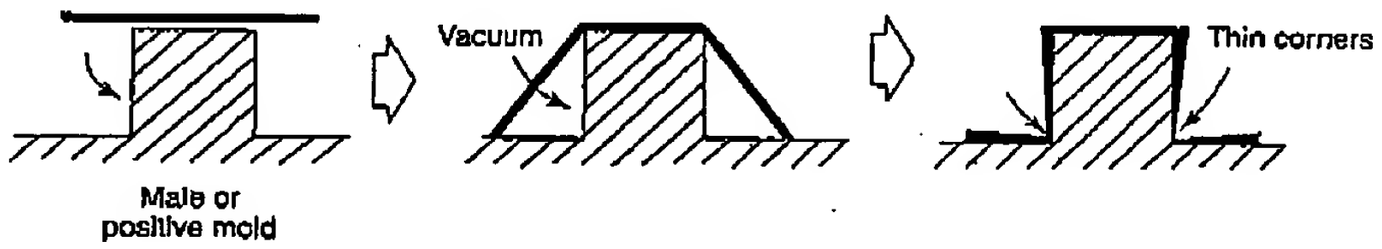


**Fig. 7.** Male or positive forming (17).

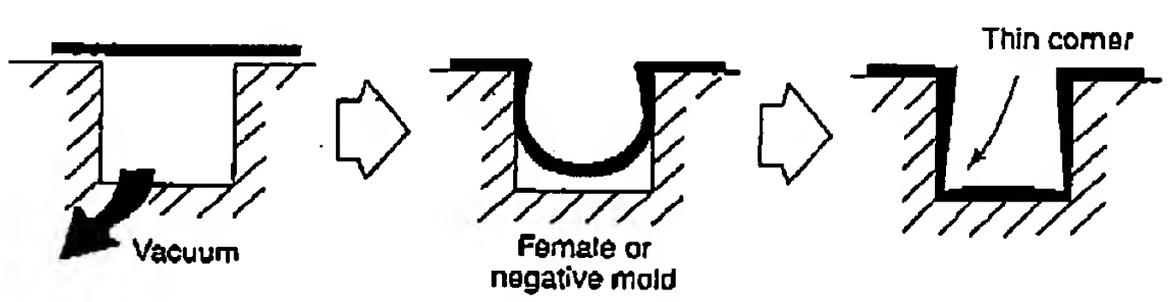


**Fig. 8.** Female or negative forming (17).

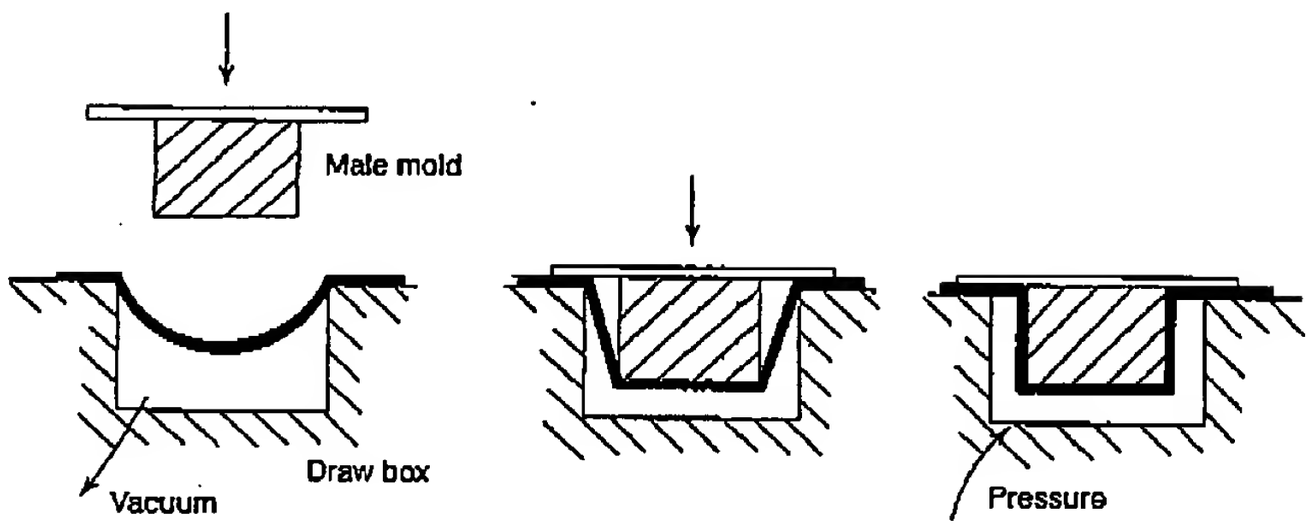


**Fig. 9.** Schematic of vacuum draw box prestretching, followed by male or positive mold insertion (18).

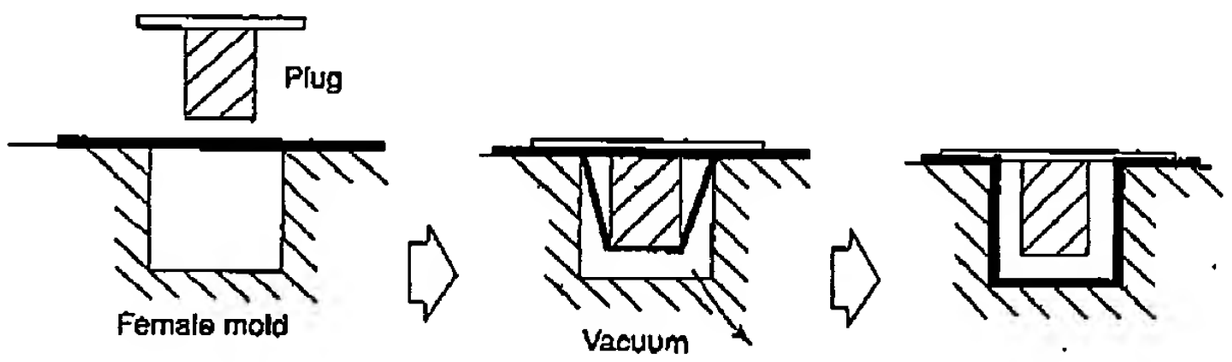


**Fig. 10.** Schematic of plug-assisted female or negative forming (18).

Prestretching is used to improve part wall thickness. Pneumatic stretching (*billow forming* or use of *vacuum draw box*; Fig. 9) is used with male molds. Mechanical stretching (*plug assist* or *push forming*) is frequently used with female molds (Fig. 10) (19). When the sheet has been stretched to near the bottom of the mold cavity, a combination of vacuum and compressed air is used to force the sheet off the plug and against the mold surface.

Pressure forming is used when the plastic is very stiff at the forming temperature, as with oriented polystyrene, when molded part requires surface detail and sharp radii or when the parts are deeply drawn. Thin-gauge pressure forming is commonly used for drink cups, deli containers, and pudding cups.

Matched mold forming is used when the plastic is very stiff at the forming temperature, as with highly filled or reinforced polymers or foamed polymers. Slip forming is used when the sheet cannot be easily stretched, as with continuous-glass reinforced polymers. During forming, the heated sheet is allowed to slide through the clamping frame. Diaphragm forming uses a heat-resistant neoprene or silicone membrane or bladder that carries the heated sheet into the mold cavity. The diaphragm is usually inflated with hot oil.

Twin-sheet forming produces hollow or semihollow parts. Both halves of a part are typically formed in female molds, and then pressed together to affect a

NOV. 13. 2007 1:39PM NO. 9183 P. 27



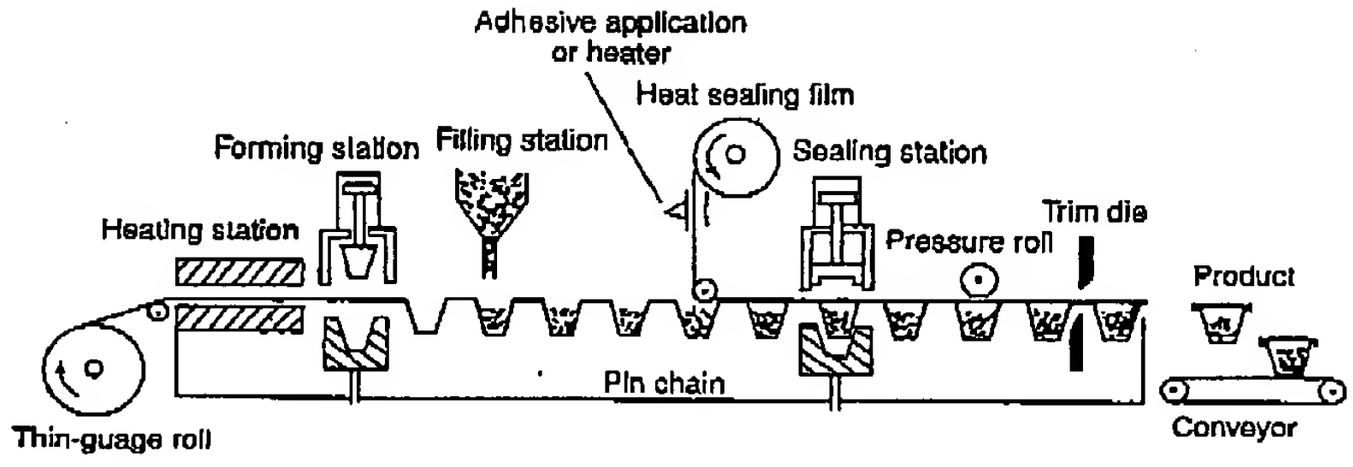


**Fig. 11.** FFS forming (19). Used with permission of Hanser Publications.

peripheral seal as well as internally welded regions. Both heavy-gauge and thin-gauge parts are twin-sheet formed.

Contact forming or trapped sheet forming is used primarily with thin-gauge FFS applications (Fig. 11) (19). The sheet is heated on one or both sides by direct contact with heated metal surface. The hot sheet is then drawn into the mold cavity. From that point, the sheet containing the formed parts is mechanically pulled through the filling, sealing, and trimming steps. Mechanical forming usually does not require a mold. The plastic sheet is machined to shape, and then locally heated and mechanically formed into the final part shape, where the open seams are glued. Cuspation also uses no mold. Instead the heated sheet is impaled at high speed with sharp projections (20). The product is a three-dimensional mat that competes with honeycomb and medium density foam.

In the 1970s, the Dow Chemical Co. developed a technique for forming shapes from sheet without the need to trim and regrind. In the scrapless thermoforming process (STP), the sheet is diced into squares (21). The squares are then coated with lubricant and heated in a conveyor oven. Each square is then placed in a forging press where it is formed into a disk. The disk is then pressure formed into an axisymmetric container. STP has merit when multilayer sheet trim cannot be successfully reprocessed. Billet forming also uses precut shapes, usually disks called billets. These are mechanically loaded into clamping fixtures that are then conveyed through an oven. Each tray containing the billets is then conveyed to a forming press where ring clamps secure the billets prior to plug-assist thermoforming into cavities. This technique is used to produce bottle liners, paint can liners, and condoms.

Heavy-gauge sheet stays at the forming temperature far longer than thin-gauge sheet or film. As a result, many more processing steps are possible with heavy-gauge sheet. The techniques are cataloged as to whether the mold is male or female, whether the sheet is prestretched with air or with a plug, and whether the stretching force is applied through pressure or vacuum (22).

Direct extrusion-to-forming is used in both thin- and heavy-gauge forming. Can lids and picnic plates are typical shallow-draw thin-gauge products produced by extruding sheet directly onto a wheel assembly that contains myriad molds. The key to quality wheel production is ensuring that the sheet is sufficiently cool

PAGE 27/45 * RCVD AT 11/13/2007 1:35:16 PM [Eastern Standard Time] * SVR:USPTO-EFXRF-1/4 * DNIS:2738300 * CSID:302 992 3257 * DURATION (mm-ss):13-50

NOV. 13. 2007 1:39PM NO. 9183 P. 28



during stretching. In heavy-gauge forming, after exiting the extrusion die, the sheet is usually cooled until somewhat rigid, then reheated in the in-line thermoformer. Since the sheet is continuous, the thermoforming machine is similar to a traditional roll-fed thin-gauge thermoforming machine. This technology is employed when production runs are long, as with refrigerator door liners.

There are three essentially separate sequential phenomenological steps in thermoforming—heating, stretching, and trimming (technically mechanical breaking or fracture).

**Heating.** Three general methods of inputting energy to sheet are convection, conduction, and radiation.

*Conduction* is energy transfer by direct contact between the sheet and a heating source. Contact heating is used when the sheets are very thin. FFS machines frequently use contact heating with the forming station being integral to the heating plate. Polymer density, specific heat (enthalpy or heat capacity), thermal conductivity, and thermal diffusivity are important in conduction. Conduction is also the method by which energy moves through the plastic sheet. Polymers are thermal insulators when compared with metals. Conduction of heat from the sheet surface to its interior is a controlling factor for heavy-gauge plastic sheets.

*Convection* is energy transfer between moving air and the plastic sheet surface. Convective heat transfer is always present since the heating sheet is surrounded by ambient air, and the free surface of the formed part is in contact with ambient or fan-driven air. Typically, energy transfer is low when the air is quiescent and only slightly higher when air is positively moved across the sheet or formed part surface. Convective hot-air ovens are used to heat very thick sheet.

*Radiation* is electromagnetic energy interchange between hot and cold surfaces in view of each other. For most thermoforming processes, most of the radiant energy is in the far-infrared wavelength range, from about 2.5 $\mu$m to about 15 $\mu$m (Fig. 12) (23). Radiant heat transfer efficiency depends on the absorbing and emitting characteristics and the relative dimensions and spacing of the heating source and the polymer material. Radiation heat transfer provides the fastest and most versatile means for heating sheet in thermoforming. The energy output from

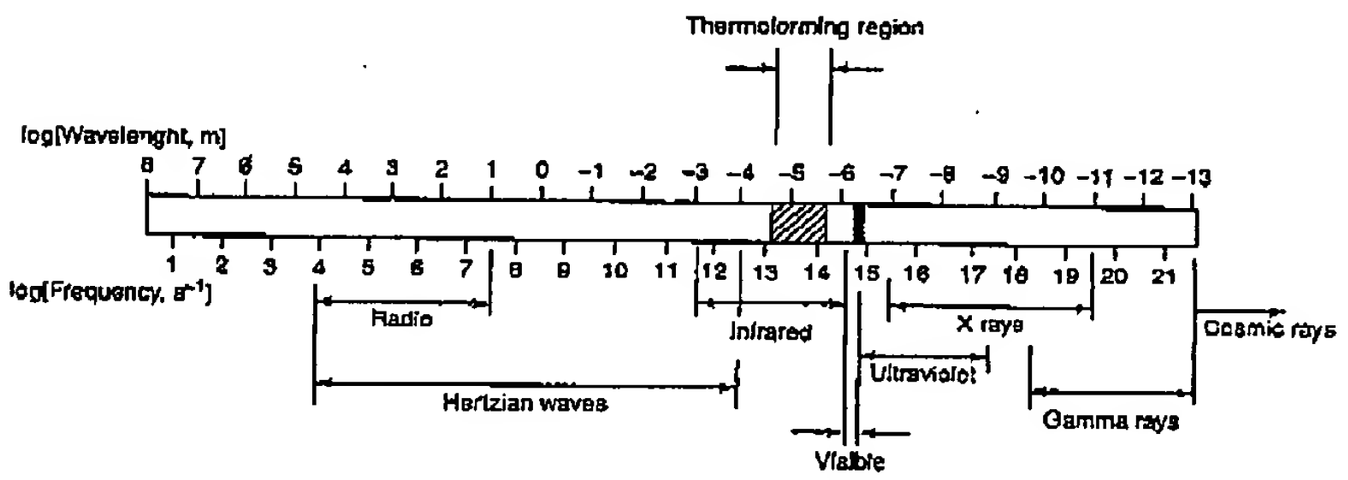


**Fig. 12.** Electromagnetic domain showing thermoforming region as portion of infrared band (23). Used with permission of Hanser Publications.

PAGE 28/45 * RCVD AT 11/13/2007 1:35:16 PM [Eastern Standard Time] * SVR:USPTO-EFXRF-1/4 * DNIS:2738300 * CSID:302 992 3257 * DURATION (mm-ss):13-50

radiant heaters is typically in the range of 30–60 kW/m$^2$ with a temperature range of 150–900°C. The common thermoforming heating sources are as follows (24):

(1) Hot air (including convection toaster ovens)
(2) Hot water/steam
(3) Sun lamps (drugstore variety)
(4) Nichrome spiral wire (such as toaster wire)
(5) Steel rod heaters
(6) Steel or nichrome tape
(7) Quartz tube heaters (nichrome wire, tungsten wire or tape)
(8) Halogen heaters (halogen-gas filled quartz tubes with tungsten wire or tape)
(9) Steel plates with embedded resistance wire
(10) Ceramic plates with embedded resistance wire
(11) Ceramic bricks with embedded resistance wire
(12) Quartz cloth heaters backed with exposed nichrome wire
(13) Steel plates that reradiate combustion energy from gas flame
(14) Steel wire grids that reradiate combustion energy from gas flame
(15) Ceramic plates that reradiate combustion energy from gas flame
(16) Indirect gas combustion on catalytic beds
(17) Direct gas combustion

Only a portion of the energy emitted by the heater actually reaches the sheet, as seen in Figure 13 (25). The selection of an appropriate heater depends on several factors:

(1) *Day-to-day running costs*. Energy costs for gas combustion heaters are about one-fourth of those for electric heaters.
(2) *Maintenance costs*. Quartz tube heaters are fragile and must be carefully cleaned. Rod heaters are rugged but can rapidly lose efficiency.
(3) *Initial installation cost*. Plate and panel heaters require less electrical connections than ceramic brick heaters. Catalytic combustion heaters require both gas and electric connections.
(4) *Heater versatility*. Quartz and halogen heaters heat very rapidly, compared with panel and catalytic combustion heaters. Ceramic brick heaters allow ease of zoning or pattern heating.
(5) *Polymer characteristics*. The sheet thickness and the polymer infrared radiation absorption characteristics may influence the heating method. Polymers with high infrared radiant transmission levels heat slower than polymers with low levels. Thin polymer sheets heat slower than thicker sheets. Polymers with higher thermal diffusivity values heat more uniformly than those with lower values. Crystalline polymers such as polyethylene and polypropylene require more energy to reach forming temperature than amorphous polymers such as polystyrene and poly(vinyl chloride) (PVC). Crystalline polymers benefit by preheating, with the preheater being placed

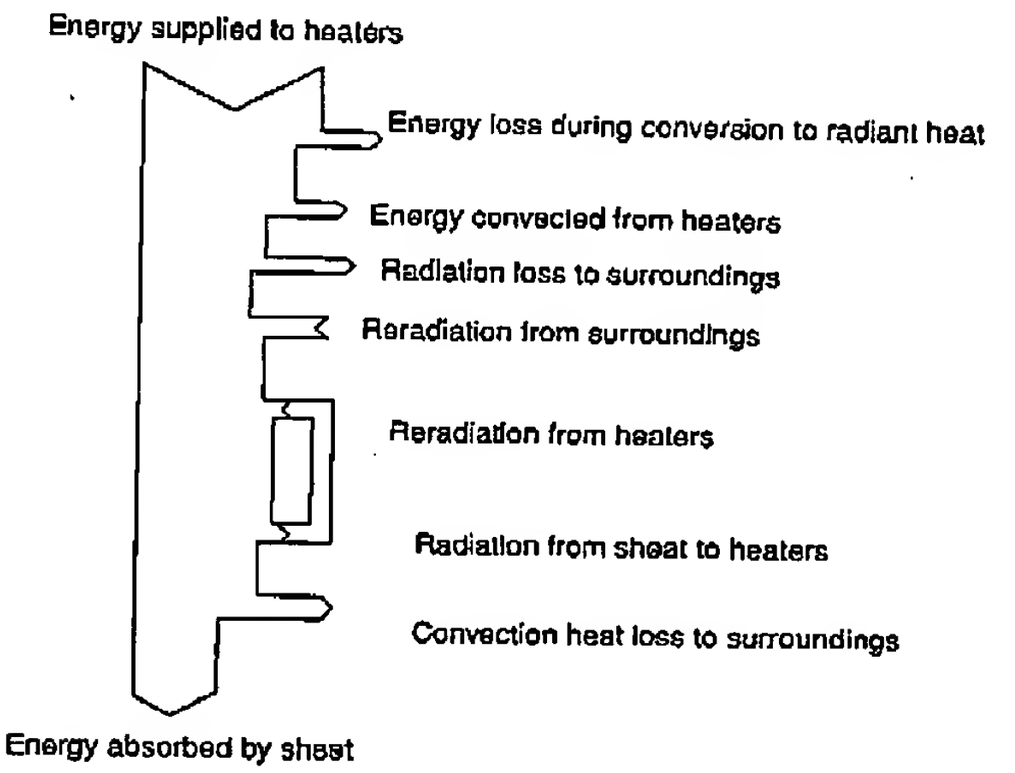


**Fig. 13.** Net energy transfer from heaters to sheet (25). Used with permission of Hanser Publications.

between the unroll stack and the pin-chain engagement on thin-gauge machines and as the first of two heaters on heavy-gauge four-station rotary thermoforming machines.

Most modern forming ovens heat sheet on both sides. Oven heater efficiency depends also on heater-to-sheet spacing, closed vs. open oven design, extent and reflective nature of nonheated surfaces, thermal protection of sheet clamping devices, heater-to-sheet area, and number of thin-gauge shots in the oven.

Sag bands or metal rods that run length of the thin-gauge oven have been used for polymers that sag excessively when heated. Some heavy-gauge shuttle thermoforming machines are equipped with ovens that completely seal the sheet between the heaters. These ovens are equipped with vacuum and compressed air, so that the sheet is lifted when it begins to sag.

**Sheet Stretching.** When the polymer sheet is at its forming temperature, it is transferred to the forming press where it is stretched against the mold surface. Technically, stretching is biaxial deformation of a nonisothermal rubbery elastic or viscoelastic membrane achieved through differential pressure across the sheet surface. Typical strain rates are up to 25 $s^{-1}$. The rubbery elastic characteristic of a polymer is described by its set of temperature-dependent stress–strain curves, as shown in schematic in Figure 14 (26).

The forming temperature region is the shaded portion. The polymer resistance to applied differential pressure and the polymer elongation at break determine the lower forming temperature. The level of sheet sag during heating determines the upper forming temperature. The maximum applied differential pressure is shown in Figure 14 as a horizontal line. The value represents the

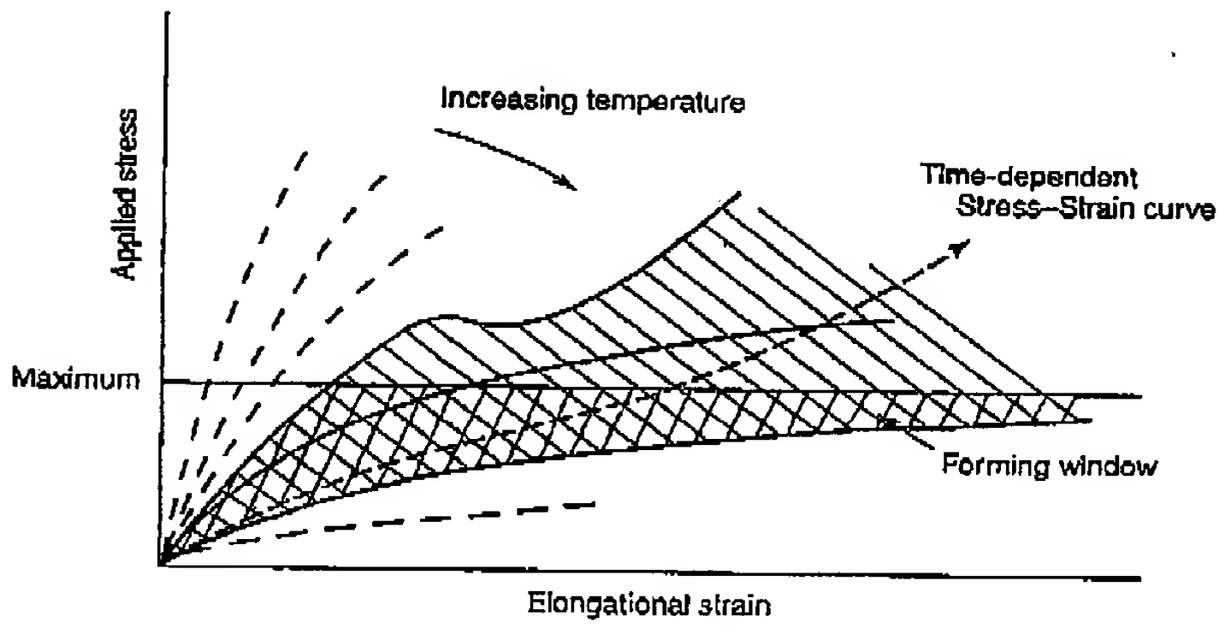


**Fig. 14.** Typical stress–strain schematic in thermoforming (26). Crosshatched region represents forming window. Used with permission of Hanser Publications.

applied vacuum in the case of vacuum forming or the extent of auxiliary air pressure used in pressure forming. The crosshatched area below this line represents the thermoforming window for a given polymer.

For most thermoforming operations using unfilled or unreinforced polymers, the differential pressure is less than 0.5–1.0 MPa (145 psi). Differential pressures of more than 3.0 MPa may be needed for high performance reinforced polymers.

Stretching against a mold surface is a differential process in that only that portion of sheet that is not in contact with the mold surface stretches. As a result, the part wall thickness varies substantially across the part surface, with the thinnest part being in the region where the sheet touches the mold last. There are two common ways of prestretching the sheet to improve wall thickness variation. In heavy-gauge thermoforming, the sheet may be prestretched using differential air pressure to inflate the sheet or draw it into a vacuum box. In both heavy-gauge and thin-gauge thermoforming, a solid shape or plug may be mechanically pressed into the sheet before differential pressure forces the sheet against the mold surface. The plug nearly uniformly draws the sheet between its bottom edge and the rim of the mold. As seen in Figure 15 (27), the effect is to pull material from the thicker regions of the part, thereby increasing the thickness of material in the region where the sheet touches the mold last.

Part wall thickness can now be predicted quite accurately with finite element analysis. The physical sheet is replaced with a two-dimensional mesh of triangular elements and nodes, which is then mathematically deformed under increasing load. When the nodes touch the electronic surface of the mold, they are affixed. Force continues to increase until all or most of the elements are rendered immobile. Currently the Ogden power-law model is used as the polymer elastic constitutive equation or response to applied load (28).

Although elastic stress–strain behavior describes sheet stretching for most thermoforming processes, sheet deformation during plug-assist prestretching is

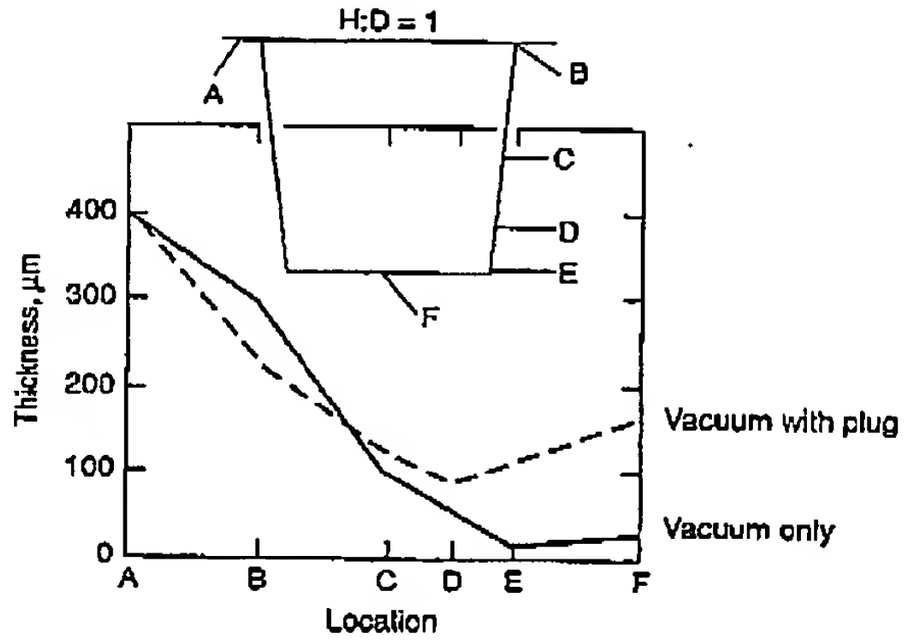


**Fig. 15.** Comparison of wall thickness variation with and without mechanical plug assist (27). Used with permission of Hanser Publications.

best described as viscoelastic. That is, the polymer responds as an elastic liquid with unrecoverable deformation occurring particularly in the contact region at the plug edge. Currently, the Kaye-Bernstein, Kearsley, Zapas model is used for the polymer viscoelastic response to applied load.

**Rigidifying the Part.** Commercial molds are temperature-controlled. In heavy-gauge thermoforming, cooling time on the mold surface may control the overall cycle time. Energy is removed from the polymer part by conduction through the single mold surface to recirculating coolant in the interior of the mold. Forced-air free-surface cooling helps reduce cooling time.

**Trimming.** *Trimming* is mechanical cutting or breaking of cooled plastic. Although there are many ways of cutting plastic, including laser and water jet cutting, most commercial thermoforming operations use either of two approaches (29). Compression cutting involves the mechanical pressing of a sharp metal edge against the plastic part. It is usually used to trim plastic less than 1.5 mm in thickness or low density foam plastic of any thickness. The sharp metal edge, usually a steel rule die, can either be pressed against an anvil or can squeeze the plastic between a forged die and a punch that has interference fit with the cutting edge (30).

Chip cutting involves mechanical breaking away of small pieces of plastic with a multitoothed blade or wheel, in a kerf between the desired part and the selvedge. It is generally used to trim plastic with thickness greater than 3 mm, and for filled and reinforced plastic. Bandsaws, hand-held drills and routers, and table-mounted circular saws are used for general cutting such as hogging the part from its trim. Computer-driven three-axis and five-axis routers are now used for more accurate trimming, especially where holes and slots must be cut into the part. The parts are usually tightly held with vacuum against a rigid fixture while being trimmed. The selection of the trim bits and the depth and speed of trimming depends strongly on the polymer being cut.

**Process and Product Control.** Machine control has steadily progressed from relay clock timers to programmable logic controllers controls to all-computer controls. On-board computers not only control the process variables but also are used extensively for inventory control. Even though infrared sensors have been used for years to measure single-point sheet temperatures during oven heating, exiting sheet on temperature alone is still novel. Recent line scanning of moving sheet has enabled operators to manually adjust heaters, but feedback heater temperature control has yet to find acceptance. Thermography or two-dimensional infrared imaging of hot surfaces is invaluable in determining heater performance, sheet temperature uniformity, effect of zone heating on sheet temperature, and mold temperature uniformity. The cost of these devices is a deterrent toward their wide acceptance as process monitors.

Thin-gauge all-electric machines were first developed for aseptic and clean-room medical packaging. In addition to minimizing lubricating and hydraulic oils, machine setup, including mold siting and in-press trim die adjustment, is far easier than with partially electric systems. Touch-screen setup programs and computer control have reduced setup time. For redoing previous jobs, these adjustments are automatic.

Incoming sheet quality control is of prime importance to the thermoformer. In addition to residual sheet orientation induced during extrusion, sheet quality monitoring must include gauge thickness, squareness for cut sheet, surface gloss or texture, color and color uniformity, identification and control of defects such as pits, gels, scratches, die lines, and optical distortion, melt flow characteristics of polyethylenes and polypropylenes, crystallinity level and intrinsic viscosity of poly(ethylene terephthalate), and mechanical properties such as impact strength, tensile strength and modulus, elongation at forming temperature, and tear resistance for thin-gauge sheet. In many cases, thermoformers may accept certification of many of these parameters from either the sheet extrusion house or the polymer supplier. In some cases, the thermoformer should run his/her own tests to ensure incoming product quality (31).

Mold design accuracy and part quality assurance have benefited from computerized coordinate measuring machines. Coordinate measuring machines provide valuable information on part reverse engineering and local part shrinkage value determination. Mold and plug design and fabrication now depend on computerized design and mold manufacture. And computer numerically controlled trimming devices in heavy-gauge forming have accelerated designer and user acceptance of thermoformed parts.

## Material Characteristics

Usually if a polymer can be extruded or cast into sheet form, it can be thermoformed. Since the basic thermoforming processes use less than 1 MPa forming pressures, nearly all thermoformable polymers are unfilled or unreinforced. The thermoforming process relies on the "hot strength" of the polymer to minimize sagging during heating. As a result, most thermoformable polymers are amorphous (see AMORPHOUS POLYMERS). Styrenics,

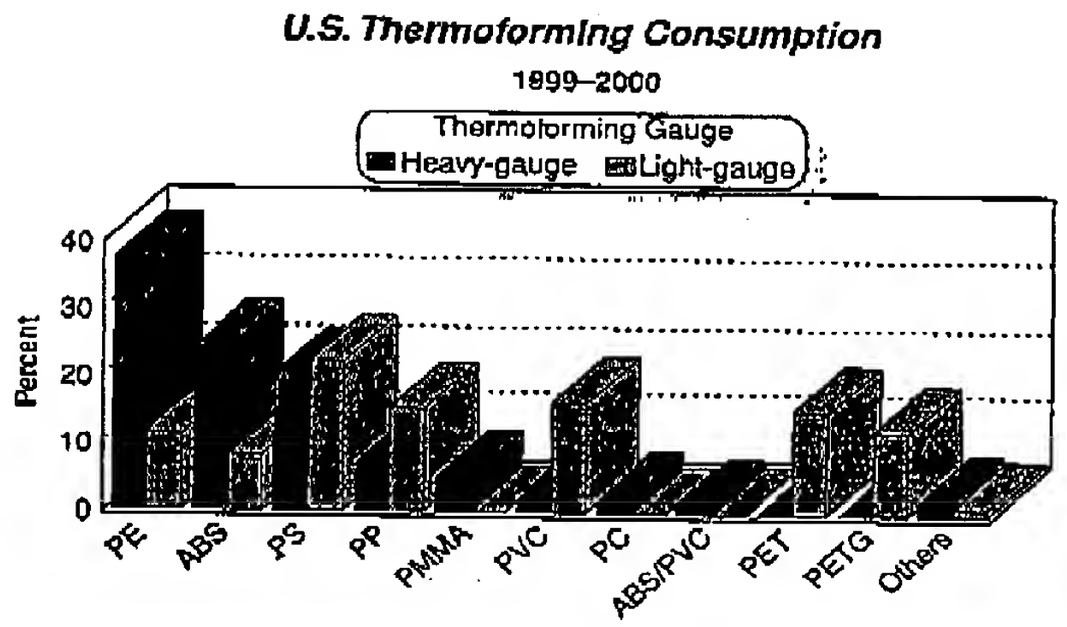


**Fig. 16.** U.S. plastic materials consumption for thin-gauge (2.1 million metric tons) and heavy-gauge (682,000 t) thermoforming (32). PE = Polyethylene; ABS = acrylonitrile–butadiene–styrene; PS = polystyrene; PP = polyproplyene; PMMA = poly(methyl methylacrylate); PVC = poly(vinyl Chloride); PET = poly(ethylene terephthalate). Redrawn and used with permission of SPE Thermoforming Division.

particularly polystyrene (see STYRENE POLYMERS) and ABS (see ACRYLONITRILE–BUTADIENE–STYRENE POLYMERS), amorphous poly(ethylene terephthalate) (see POLYESTERS, THERMOPLASTIC) [APET], PVC (see VINYL CHLORIDE POLYMERS), poly(methyl methacrylate) (see METHACRYLIC ESTER POLYMERS) [acrylic], and polycarbonates (qv) are commonly thermoformed. The only crystalline polymer in wide use is high density polyethylene, which has excellent elasticity in the melt state (see ETHYLENE POLYMERS, HDPE; SEMICRYSTALLINE POLYMERS). Newer grades of polypropylene are being designed specifically for thermoforming. Figure 16 shows current U.S. polymer usage in both thin-gauge and heavy-gauge thermoforming (32).

In addition to "hot strength" or elasticity at the forming temperature, other intrinsic polymer characteristics are important in thermoforming. The chemical makeup of the polymer dictates the extent of infrared energy absorption or its counterpart, infrared energy transmission. At the same thickness, polyethylene has a higher infrared transmission level and therefore lower radiant energy absorption than polystyrene. This is seen by comparing the infrared spectra of polyethylene (Fig. 17) and polystyrene (Fig. 18) (33). As expected, the fraction of energy transmitted through the polymer film decreases with increasing film thickness. Infrared energy transmission spectra are usually available from polymer material suppliers.

The forming window for a given polymer can be quantified by differential thermal mechanical analysis. Specifically, the temperature-dependent elastic modulus is key, as shown in Fig. 19, for typical thermoformable polymers (34). An adequate forming window is dictated if the modulus curve shows a flattening or

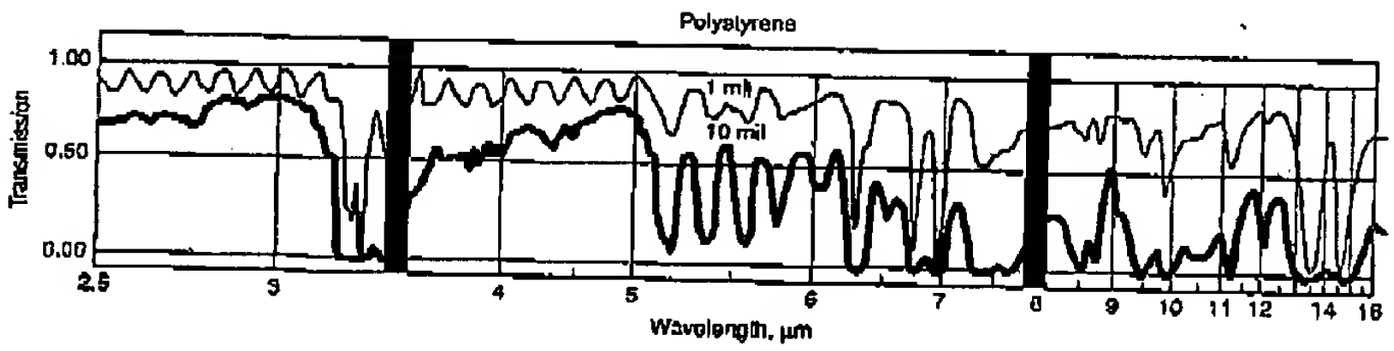


**Fig. 17.** Infrared transmission spectrum for two thicknesses of polystyrene (33). 1 mil = 25.4 $\mu$m. Used with permission of Hanser Publications.

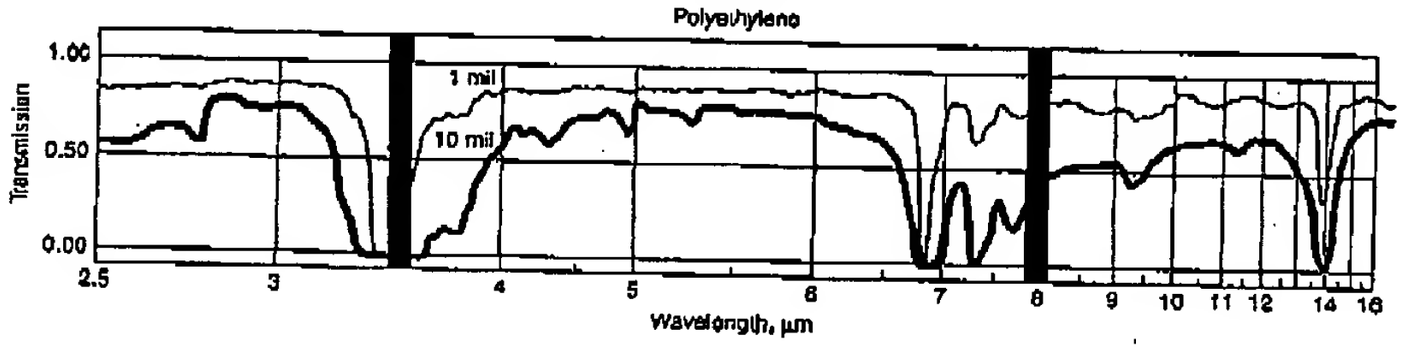


**Fig. 18.** Infrared transmission spectrum for two thicknesses of polyethylene (33). 1 mil = 25.4 $\mu$m. Used with permission of Hanser Publications.

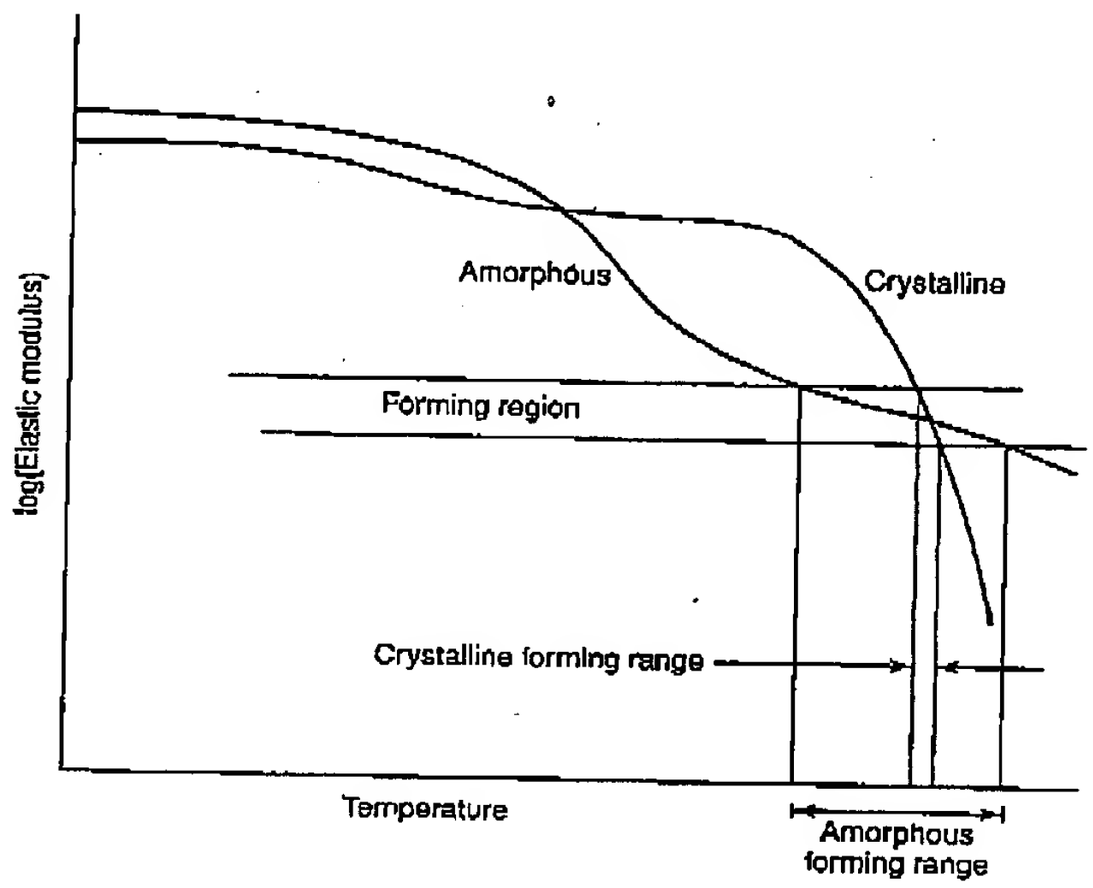


**Fig. 19.** Typical temperature-dependent elastic moduli of an amorphous and a crystalline polymer, showing forming regions for both (34).

plateauing at a value range consistent with normal thermoforming differential pressure. If the polymer modulus curve shows little flattening or if the flattening occurs at a very low value, the polymer may have a small forming window or none at all. If the flattening occurs at a very high value, normal forming pressures may be inadequate to stretch the polymer into detailed or complex molds.

Polymer thermal properties, such as temperature-dependent specific heat or enthalpy, thermal conductivity, and thermal diffusivity are also important. Although thermoforming is a thermally and mechanically gentle process insofar as the polymer is concerned, the general process of extrusion, thermoforming, regrinding, and potentially multiple reextrusions may lead to extensive molecular damage (35). This is particularly true with thermally sensitive polymers such as PVC and poly(ethylene terephthalate). Thus intrinsic polymer thermal stability and thermal and mechanical stability of the additives must be considered.

By far the majority of sheet formed does not contain fillers or reinforcing fibers. Fillers and fibers increase polymer stiffness but usually not polymer transition temperatures. Polymers containing up to 40 wt% talc, calcium carbonate, glass cullet, and diatomaceous earth are typically pressure formed at higher than usual temperatures. Polymers containing moderate levels of chopped glass and carbon fiber and certain types of nonwoven fibers are also pressure formed or matched mold formed. Fillers and fibers affect the radiative and thermal properties of the sheet. Organic dyes used to color transparent polymers usually do not affect the radiative characteristics of the polymers. Inorganic pigments have particle sizes that may interfere with volumetric radiant absorption.

And although thermoforming is basically a rubbery solid deformation process, the viscoelastic character of the polymer may need to be understood, particularly for the plug-assisted forming process. Computer-aided design programs also may need polymer viscoelastic properties. This may be particularly true for crystalline polymers such as polyethylene and polypropylene when formed above their melt temperatures. This is discussed below.

Excessive and/or inconsistent residual orientation in polymer sheet induced during the extrusion process can be a vexing problem in thermoforming. Thermoformers work with extruders to keep both machine-direction and cross-direction orientations to 5% or less. Table 3 gives advantages and disadvantages of several thermoformable polymers.

## Mold Materials

Since thermoforming is a low pressure process, production molds are made of soft metals such as aluminum (36). Very large heavy-gauge molds and some thin-gauge molds are commonly sand-cast of A356 aluminum. Multicavity thin-gauge molds and some smaller heavy-gauge molds are machined from A6061 aluminum. For polymers requiring higher forming temperatures, such as polysulfones (qv) or polycarbonates (qv), machining grade A7075 aluminum is used. Machined 316 stainless steel is used on occasion for corrosive polymers such as rigid poly(vinyl chloride). Electroformed nickel molds are used when extreme mold detail is required. Regions far from cooling sources may be made of higher thermal conductivity metals such as copper–aluminum alloy or bronze. Pinch-off areas may be

Table 3. Advantages and Disadvantages of Thermoformable Polymers[a]

| Polymer | Processing temperature range, °C | Advantage | Disadvantage |
|---|---|---|---|
| Polystyrene (TG) | 150–190 | Easily formed<br>Inexpensive<br>Easily extruded | Brittle<br>Tenacious trim dust<br>Plug mark-off |
| High-impact polystyrene (HG, TG) | 160–205 | Available<br>Good impact<br>Easily colored | Limited elongation<br>Yellows at high temp<br>May smoke |
| ABS HG) | 150–205 | Great toughness<br>Easily formed | Hazy, translucent<br>Absorbs moisture<br>Yellows at high temp<br>Splitty at low temps<br>FR grades stiff |
| Modified polyphenylene oxide (HG) | 165–220 | Forms like HIPS<br>Fire-retardant<br>Great pressure-formed | Stiff at mod temps<br>Odor at forming temp<br>Usually trim cold<br>Tenacious trim dust |
| Oriented polystyrene (TG) | 130–160 | Superior surface gloss<br>Great impact strength<br>Great opticals | Careful heating<br>Trimming difficult<br>Expensive<br>Direct contact heating |
| Poly(methyl methacrylate) (acrylic) (HG) | 150–205 | Great gloss<br>Readily formed<br>Excellent UV | Somewhat moisture sensitive<br>Easily scratched<br>Brittle in sharp corners |
| Poly(methyl methacrylate)/poly(vinyl chloride) (HG) | 150–190 | Great pressure-formed<br>Good fire retardancy | Yellow at high temps<br>Brittle in trimming<br>Good outdoor appl. |
| Extra tough polymer (hg, TG) | 150–180 | Good toughness<br>Good clarity<br>Good chem. resistance | Expensive<br>Not normally a stock item |
| Flexible PVC (hg, TG) | 105–150 | Good drawability<br>Fire retardant<br>Good automotive matl | Weak at high temps<br>Plasticizer odor<br>Grain wash at high temps |
| Rigid PVC (HG) | 120–180 | Fire retardant<br>Easily colored<br>Tough<br>Moderate transparency<br>Outdoor appl. | Yellows at high temps<br>Low $T_g$<br>Difficult prestretch<br>Narrow processing window<br>Recycle times limited |

Table 3. (Continued)

| Polymer | Processing temperature range, °C | Advantage | Disadvantage |
|---|---|---|---|
| Low density polyethylene (TG) | 125–175 | Tough | Poor high temp char. |
| | | | Excessive sag |
| | | | Narrow forming window |
| | | | Haze at high temps |
| | | | Sticky on plugs |
| High density polyethylene (HG) | 140–195 | Tough | Excessive sag |
| | | Good melt strength | Black heats fast |
| | | Fractional melt index | |
| Polypropylene (hg, TG) | 145–165 | Tough | Narrow forming window |
| | | High temp appl. | Excessive sag |
| | | Can be transparent | Plug mark-off |
| | | Best pressure-formed | Can be sticky |
| | | Heavy-gauge matls now | Whiskers during trimming |
| EP copolymer (TG) | 130–180 | Forms like high denisty polyethylene | Sags at high temp |
| | | Forms best cool | Clean trim difficult |
| Oriented polypropylene (TG) | 145–160 | Very low haze | Expensive |
| | | High gloss | Must be heated very carefully |
| | | Great impact strength | Sags, loses orientation |
| | | Contact heat best | |
| Ethylene–vinyl acetate (TG) | 135–150 | Draws well | Easily torn |
| | | | Narrow forming window |
| Polypropylene – –20% talc (hg, TG) | 150–205 | Forms well | Stiff at forming temp |
| | | Plug desired | Low elongation at high temp |
| | | Best pressure-formed | Matte surface |
| Polypropylene – –40% glass-reinforced (HG, tg) | 150–230 | Best pressure-formed | Very stiff at forming temp |
| | | | Shallow draw best |
| | | | Plug assist questionable |
| Polycarbonate (HG) | 180–230 | Great UV resistance | Stiff at forming temp |
| | | High temp appl. | Moisture sensitive |
| | | Good forming window | Trim very difficult |
| | | Good colors | |

Table 3. (Continued)

| Polymer | Processing temperature range, °C | Advantage | Disadvantage |
|---|---|---|---|
| Amorphous poly(ethylene terephthalate) (TG) | 125–165 | Tough thin-gauge | Sags, necks |
| | | Orients, toughens | Crystallizes rapidly |
| | | Transparent | Difficult cold trim |
| | | | Trim must be recrystallized |
| Crystallizable poly(ethylene terephthalate) (TG) | 185–200 | High temp appl. | Mold temp control |
| | | | Very stiff when hot |
| | | | Crystallinity control difficult |
| | | | Brittle when too crystalline |
| Glycol-modified poly(ethylene terephthalate) (HG, TG) | 160–180 | Good toughness | Somewhat costly |
| | | Good colors | Limited sourcing |
| | | Good forming window | Can yellow at high temp |
| | | | Not good outdoor matl |
| Cellulosics (TG) | 140–165 | Excellent clarity | Expensive |
| | | Great toughness | Lost market to PVC, PET |
| | | Good forming window | Somewhat moisture sensitive |
| | | | Limited availability |
| Thermoplastic elastomer (TG) | 185–180 | Draws well | Spring-back |
| | | Many versions to choose | High rubber difficult |
| | | Automotive darling | May tear at high temp |
| | | | Grain wash at high temp |

[a]Key: HG = major heavy-gauge; TG = major thin-gauge; hg = minor heavy-gauge; tg = minor thin-gauge; no notation, not normally used.

made of carbon steel. Gaskets in pressure boxes are usually made of neoprene or silicone.

Thermoforming is one of the major processes used to produce prototype parts that may be made other ways, such as injection molding. Many materials are used to produce molds that are serviceable for a few to a few hundred parts. Traditional mold materials include wood, plywood, hard plaster such as Hydrocal (US Gypsum), and medium density fiberboard. Sprayed and cast white metal are used on occasion.

Recently, prototype molds are being fabricated from particle-filled polyurethane and epoxy syntactic foams using computer-aided multiaxis routers. Plugs, used to mechanically prestretch polymer sheet, are also usually machined from syntactic foams. For certain polymers, heated aluminum plugs or solid nylon plugs are desired.

## Part Design

In general, thermoforming may be described as a differential stretching process. The sheet free of the surface continues to thin as it is drawn against the mold surface. As a result, the thickest portion of the part is where the sheet touches the mold first and the thinnest is where the sheet touches the mold last. Prestretching techniques move sheet from the thicker areas to the thinner ones, but in general, thermoformed parts have nonuniform wall thicknesses. Female parts tend to have thicker rims and thinner two- and three-dimensional corners. Male parts tend to have thicker two- and three-dimensional corners and bottoms and thinner rims. Multicompartment parts with both male and female sections, sometimes called androgynous parts, require careful mold design and proper sizing of plugs to minimize very thin sidewalls and internal webbing and to provide adequate internal draft angles.

Recently, computer-aided design programs have been devised that allow prediction of part wall thickness (37,39). These programs use finite element analysis, with the sheet being characterized as a two-dimensional mesh of nodes forming triangular elements. Although the earliest programs used Mooney-Rivlin constitutive equations of state to describe purely elastic polymer response to the applied differential load, current programs use the doubly infinite semiempirical Ogden model, with the series truncated at two or four elements. The K-BKZ constitutive model is used to describe viscoelastic behavior (39). An example of a computer-generated thickness profile is given as Figure 20.

Computer-aided wall thickness prediction is compromised by measured variation in actual part wall thickness due to the practical intrinsic variation in processing parameters, as seen in Figure 21 for thin gauge parts and Figure 22 for heavy-gauge parts (40).

Distortion-printed products have been used since World War II (41). Until recently, the standard technique involved thermoforming a polymer sheet to the desired shape, painting the desired design on the shape, and then reheating the shape to a flat sheet. This has been largely replaced with finite element computer programs that carry out the entire process electronically.

Most amorphous polymers linearly shrink about 0.4–0.6%. Crystalline polymers such as high density polyethylene and polypropylene linearly shrink about 2.0% (42). Thermoformed parts shrink away from female molds and onto male molds. Male molds must have typical draft angles of 2–5°, but sufficiently great enough to allow release of the formed parts. Female molds need minimal, if any, draft angles.

Many thermoformed parts contain undercuts. Detents and interlocking lugs are frequently used in thin-gauge packages with integral lids. Undercuts in

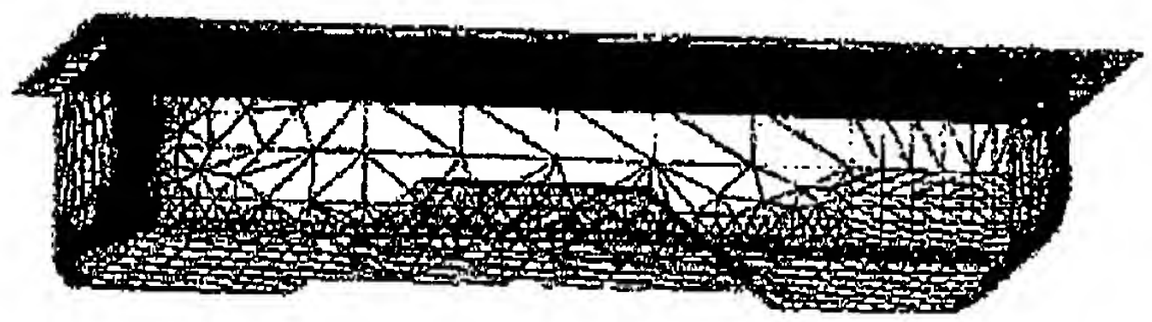


**Fig. 20.** Finite element analysis of local wall thickness for drawdown into negative mold (39). Used with permission of Institut für Kunststoffeverarbeitung, Aachen, Germany.

heavy-gauge parts are achieved with swing-away sections that are either manually or pneumatically activated (43).

Holes are machined into heavy-gauge parts in the post-forming, trimming operation. Holes are punched into thin-gauge parts just prior to cutting the parts from their web.

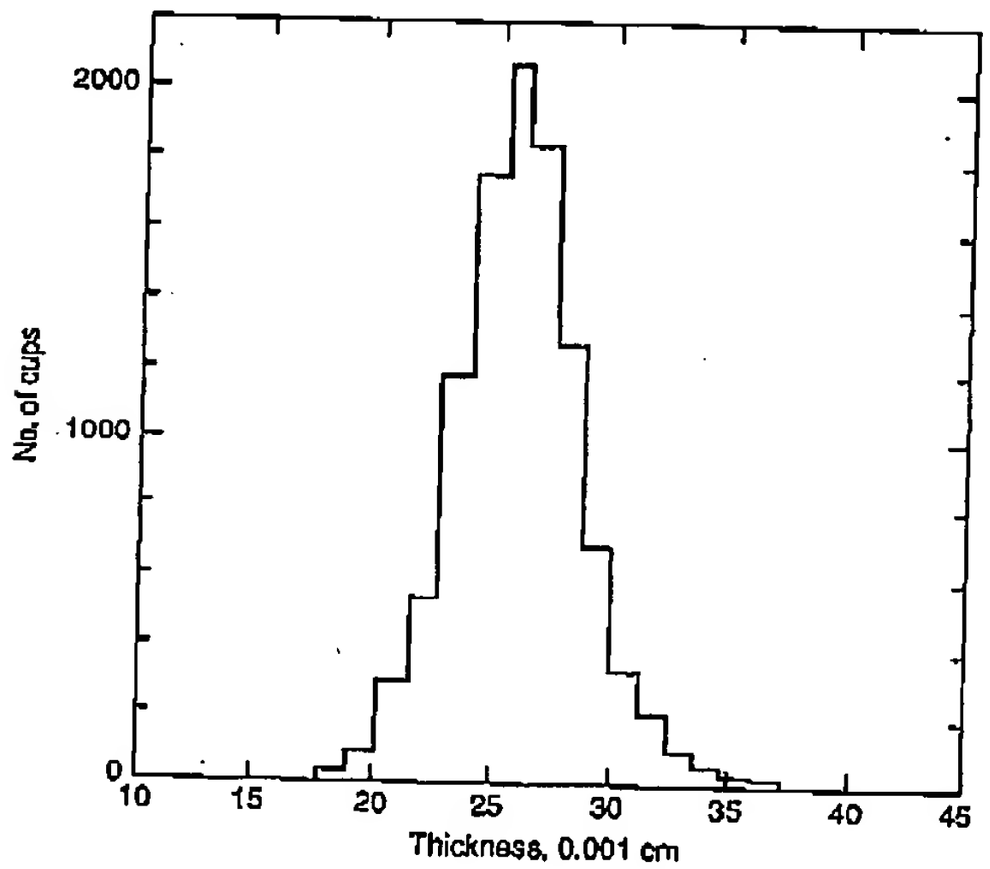


**Fig. 21.** Side wall thickness variation during normal production—thin-gauge thermoformed cup (40). Redrawn and used with permission of SPE Thermoforming Division.

## Newer Technologies

Twin-sheet thermoforming is more than a century old. Recent interest in returnable shipping pallets has rekindled this heavy-gauge technology. The competition is rotational molding and blow molding, major technologies for producing hollow parts. Twin-sheet forming forte lies in manufacturing high aspect ratio parts with many welded areas, such as shipping pallets, backboards, tabletops, and door panels. The key to quality twin-sheet parts is the integrity of the seal area between the two formed plastic sheets. This is particularly important in sequential forming, where the first formed plastic sheet resides on its mold half while the second sheet is being formed. High density polyethylene is the preferred polymer, since it remains tacky throughout this interval. Rigid PVC and ABS have also been twin-sheet formed economically. Although the earliest twin-sheet parts were of thin gauge, interest is only recently been rekindled in this area, with commercial successes in medical devices and liquid containers.

Multilayer polymer film and sheet are thermoformed into packages when moisture, odor, and/or oxygen barriers are needed. A typical multilayer package consists of a rigid outer polymer such as polystyrene, followed by an adhesive layer, an oxygen barrier film such as ethylene vinyl alcohol, another adhesive layer, and a moisture barrier inner polymer such as polyethylene or polypropylene. Although multilayer films and sheets are relatively easy to thermoform, the growth in the market has been limited by the difficulty in reprocessing the trim.

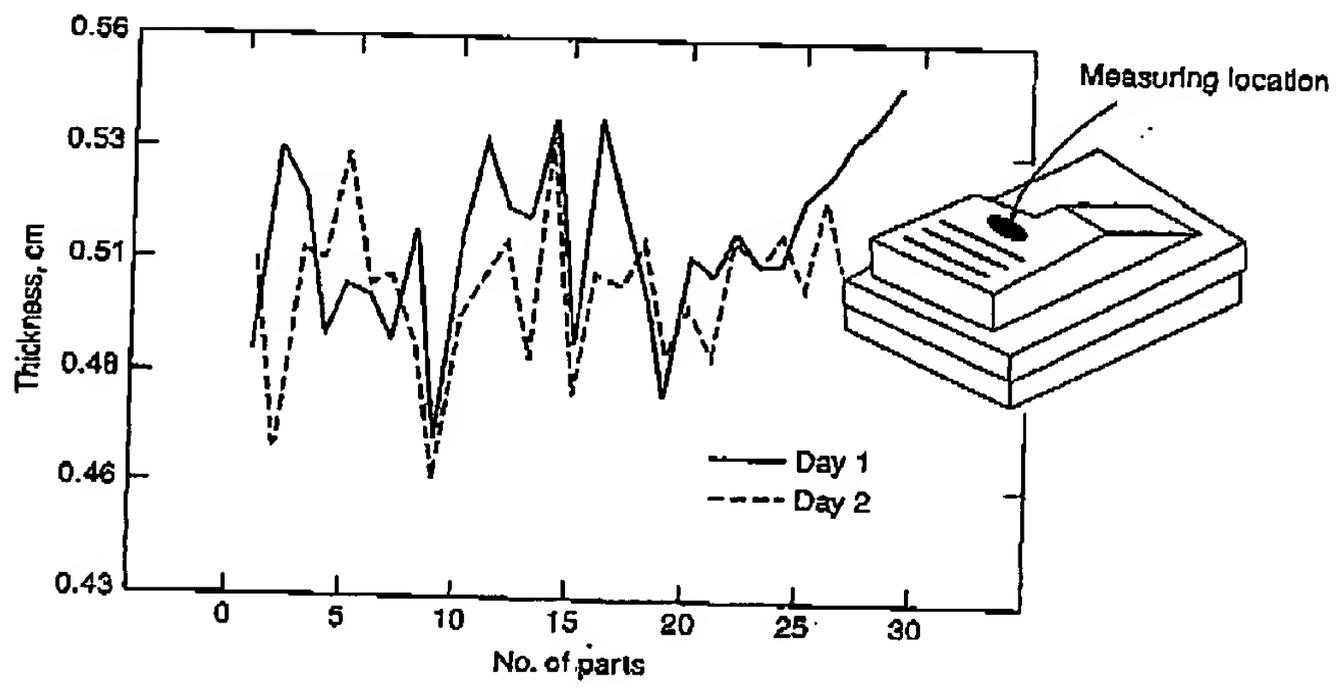


**Fig. 22.** Bottom wall thickness variation during normal production—heavy-gauge thermoformed part (41). Redrawn and used with permission of SPE Thermoforming Division.

Thermoplastic foam sheet of polystyrenics or polyolefins are thermoformed into impact resistant packages. Typically, care must be taken to avoid overheating low density foam sheet. Foams are usually quite stiff at forming temperatures and matched mold tooling is normally used to achieve reasonable draw ratios (44). For advanced applications where the packages must act as both rigid containers and moisture absorbers, mechanical, thermal, and phase separation means are used to open foam cells. These foams are usually formed at higher temperatures on single-surfaced molds. Even when foamed, polylactic acid and polystarch derivative polymers thermoform well into compostable or degradable containers.

Heavy-gauge thermoforming owes much of its continuing success against injection molding to the adaptation of computer numerically controlled routers from the woodworking industry (16). Computer-controlled routing has allowed accurate nonplanar trim lines, reproducible slotting, and accurate hole drilling.

Even though lightly filled polymers have been thermoformed for decades, the majority of the sheet formed contains no fillers or fibers. Recent developments in forming reinforced thermoplastic sheet include a thermoformed all-composite bumper assembly for BMW (Jacob Composite GmbH, Dresden, Germany, 2002) and composite bed leaf springs (45). Currently, glass-reinforced polypropylene and nylons are the preferred polymeric materials. This work is being spurred by newer technologies in heating and bending the less-extensible sheet.

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## TRANSITIONS AND RELAXATIONS.

See VISCOELASTICITY.

## TRIBOLOGICAL PROPERTIES OF POLYMERS.

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